Global Modeling Plans at NCEP

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The Next GFS in 2016:

4DHybrid EnVAR

- ***4D hybrid ensemble-variational data assimilation:*** **The ensemble provides an updated estimate of situation dependent background error every hour as it evolves through the assimilation window. This flow dependent statistical estimate is combined with a fixed estimate.**

- **Improved use of satellite radiances**

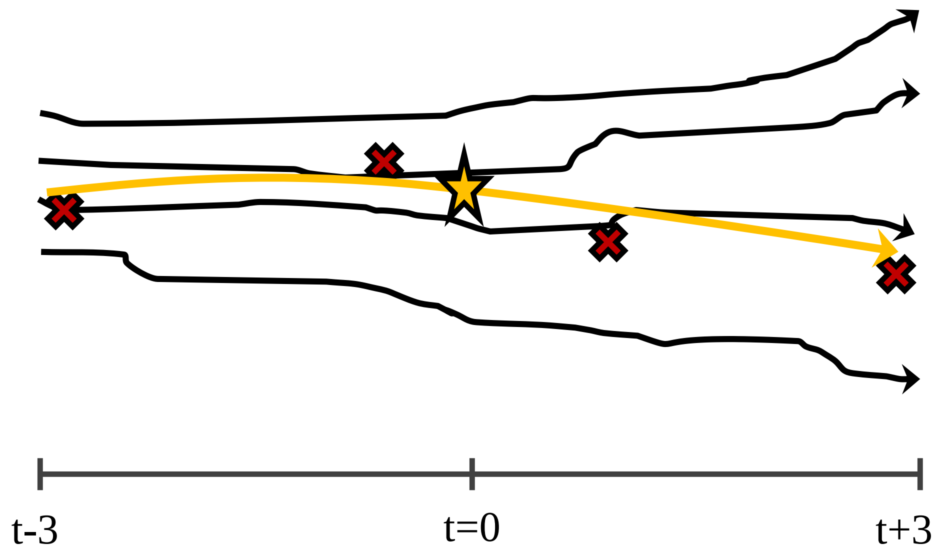
- **Improved use of satellite winds and aircraft observations**

- **Corrections to land surface to reduce summertime warm, dry bias over Great Plains**

Major Components

- 4-D hybrid
- All-sky AMSU-A Radiances
- SATWND ob changes
- CRTM v2.2.1
- Aircraft ob changes
- Modified thinning/weight in time
- Bug fixes and optimization for GSI
- New ob monitoring
- Upgrade data assimilation monitoring package

4D Schematic



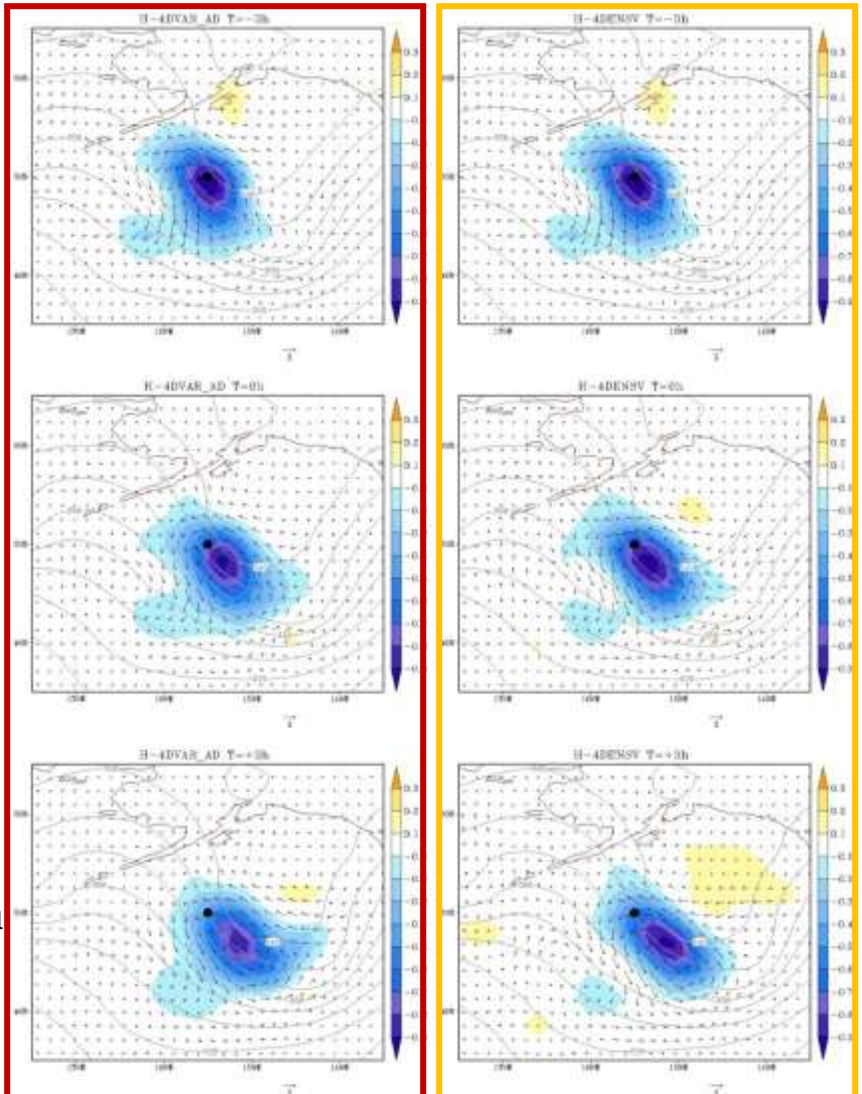
- 4D increment constructed by figuring out best combination of 4D ensemble perturbations
- Weights constant throughout window
- Use temporal correlations within each member to extract time information in observations

Time Evolution of Increment

t=-3h

t=0h

t=+3h



H-4DVAR_AD **H-4DENSV**

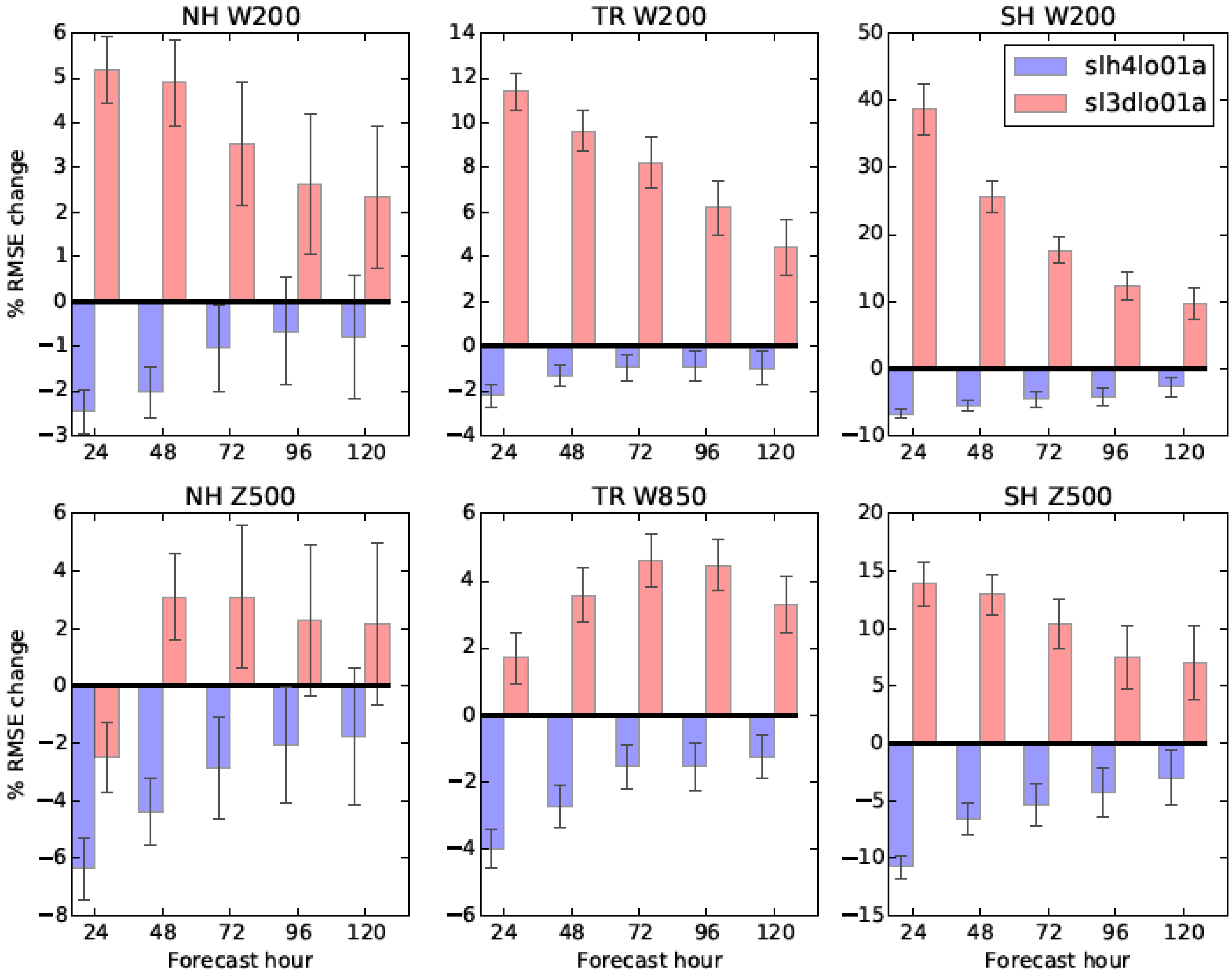
Solution at beginning of window same to within round-off (because observation is taken at that time, and same weighting parameters used)

Evolution of increment qualitatively similar between dynamic and ensemble specification

** Current linear and adjoint models in GSI are computationally unfeasible for use in 4DVAR other than simple single observation testing at low resolution

4-D hybrid

- Outer/inner iterations (2/(50,150))
- Variational QC turned on after 25 iterations
- TLNMC on
- DFI on in ensembles
- IAU or DFI off/on in high resolution
- Ozone cross covariances on
- Localizations changes – ½ reduction in troposphere
- Static/Ensemble weights from 25/75% to 12.5/87.5%
- Additive error inflation removed from EnKF



4d-hybrid
3d-var

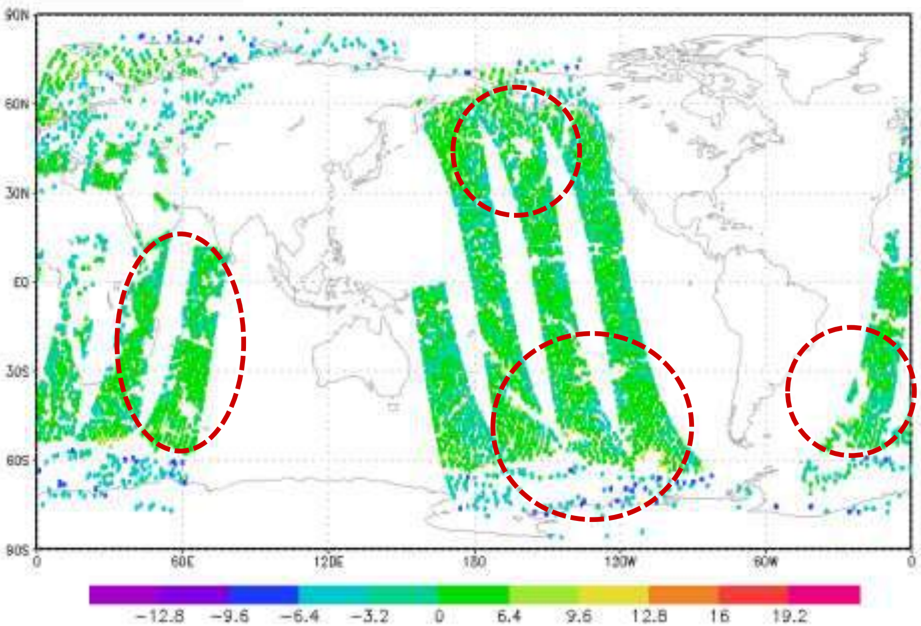
Both compared to 3d-hybrid

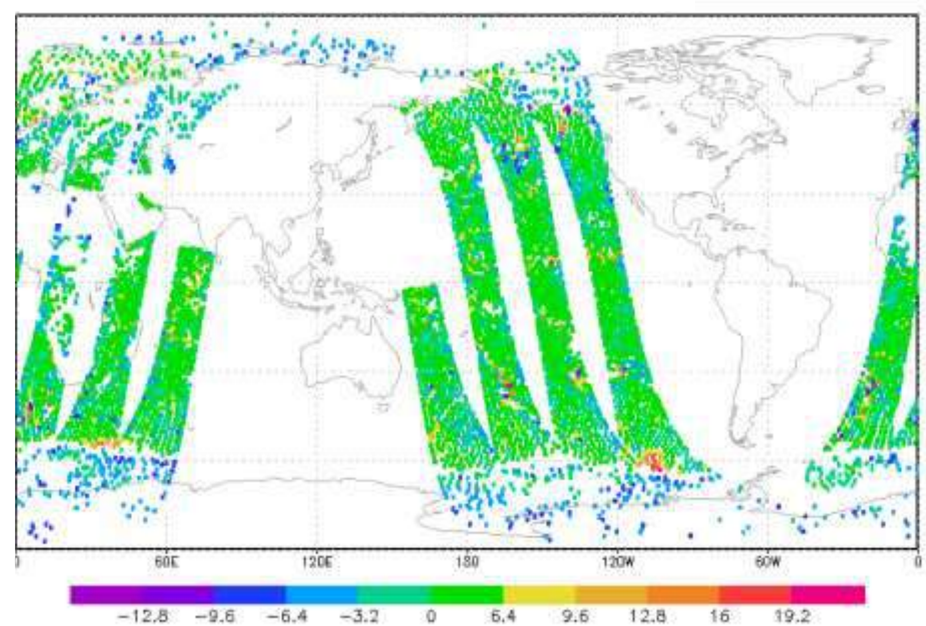
Motivation slide for going from 3-D to 4-D

All-sky AMSU-A Radiances

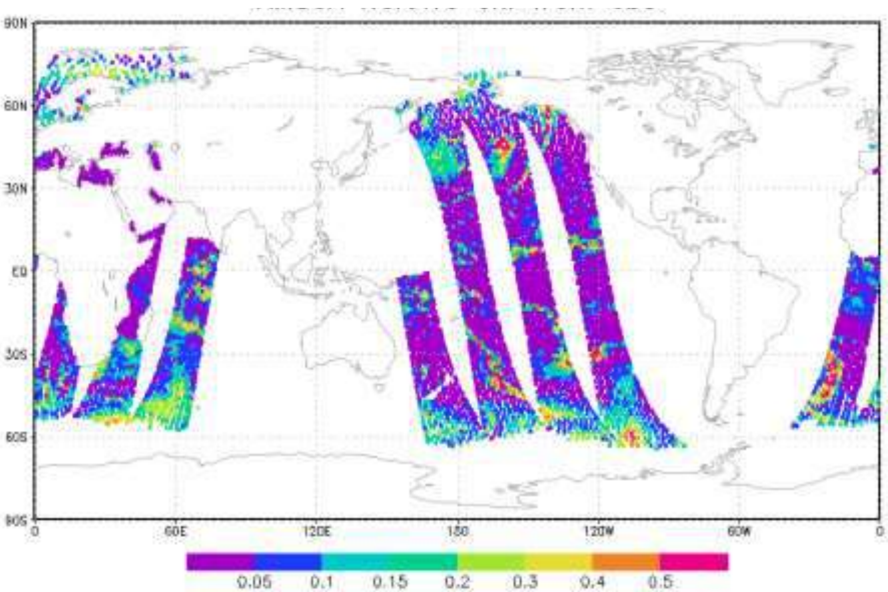
- Situation-dependent observation error inflation; AMSU-A observation error re-tuned;
- All-sky radiance bias correction strategy (Zhu et al. 2014)
- Additional quality control: cloud effect (Geer et al. 2013) and emissivity sensitivity screening;
- Normalized cloud water control variable; New static background error variance and correlation lengths for cloud water; Non-zero Jacobian where cloud amount is zero;
- Validation and improvement of the CRTM;
- Other changes and bug fixes
- Many experiments performed, all results neutral to slightly positive
- Only initial implementation of this capability

Clear-sky OmF vs. All-sky OmF





CLW



- More data coverage: Thick clouds that are excluded from clear-sky assimilation are now assimilated under all-sky configurations
- Rainy spots are excluded from both configurations

AMSUA NOAA19 CH1 00Z 20131029

Warm, dry bias over Great Plains

- **late July and early August many complaints from field offices**
  - **GFS too warm and too dry particularly over the Great Plains.**
- **noticed last summer in the parallel GFS**
  - **some parameters were refined to address the issue.**
- **Extensive sensitivity tests --refinement significantly reduced the warm/dry biases**
  - **too late to put into the last January GFS implementation.**
- **further tests conducted with proposed parameter changes.**
  - **Rerun this summer (forecast only)**
  - **Rerun this summer with land and analysis changes (analysis and forecast)**
  - **Rerun this summer with land changes only (analysis and forecast)**

Parameter refinements

- rsmin for grassland from 45 to 20
- rsmin for cropland from 45 to 20

$$C_h = \frac{k^2/R}{[\ln(\frac{z}{z_{0m}}) - \Psi_m(\frac{z}{L}) + \Psi_m(\frac{z_{0m}}{L})][\ln(\frac{z}{z_{0t}}) - \Psi_h(\frac{z}{L}) + \Psi_h(\frac{z_{0t}}{L})]}$$

Smaller rsmin (Rc_min) resulting higher evaporation

$$Rc = \frac{Rc\_min}{LAI\, F_1 F_2 F_3 F_4}$$

- Where:
  - LAI: leaf area index
  - Rc_min ≈ f(vegetation type)
  - F1 ≈ f(amount of PAR:solar insolation)
  - F2 ≈ f(air temperature: heat stress)
  - F3 ≈ f(air humidity: dry air stress)
  - F4 ≈ f(soil moisture: dry soil stress)

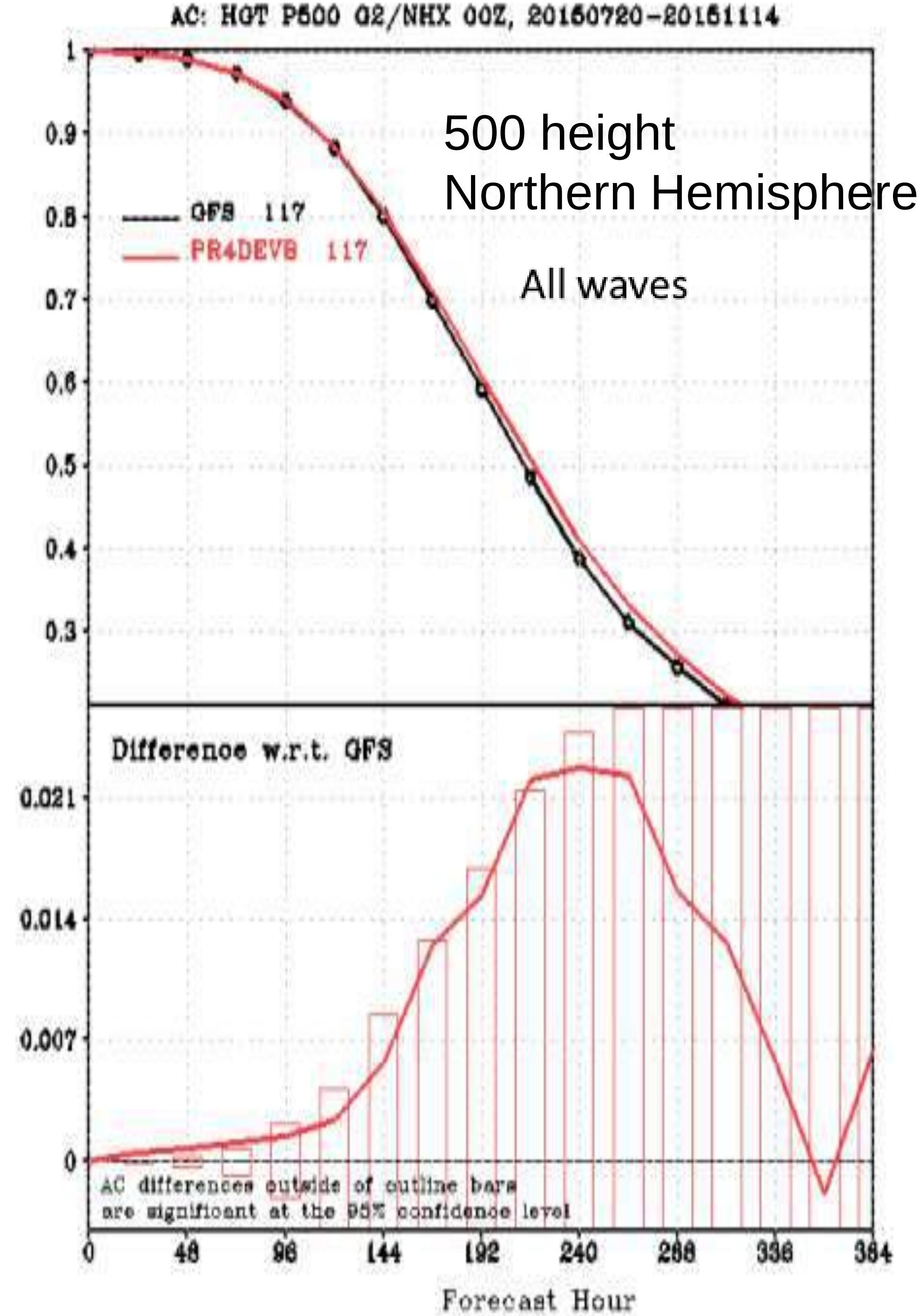
- Surface fluxes are more sensitive to the treatment of roughness length for heat/moisture than to M-O based surface layer schemes themselves (Chen et al. 1997)

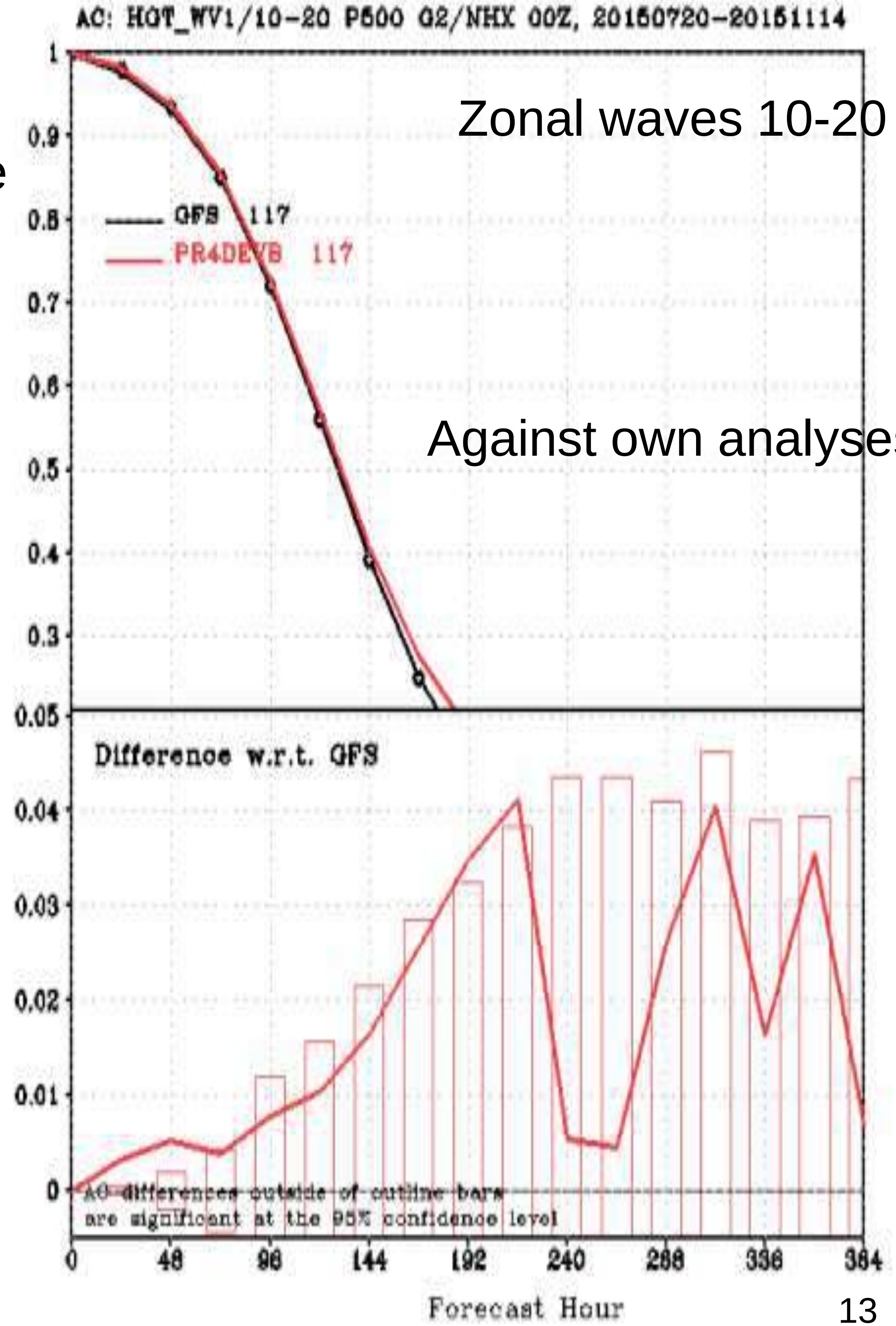
- Treatment of roughness length for heat and moisture

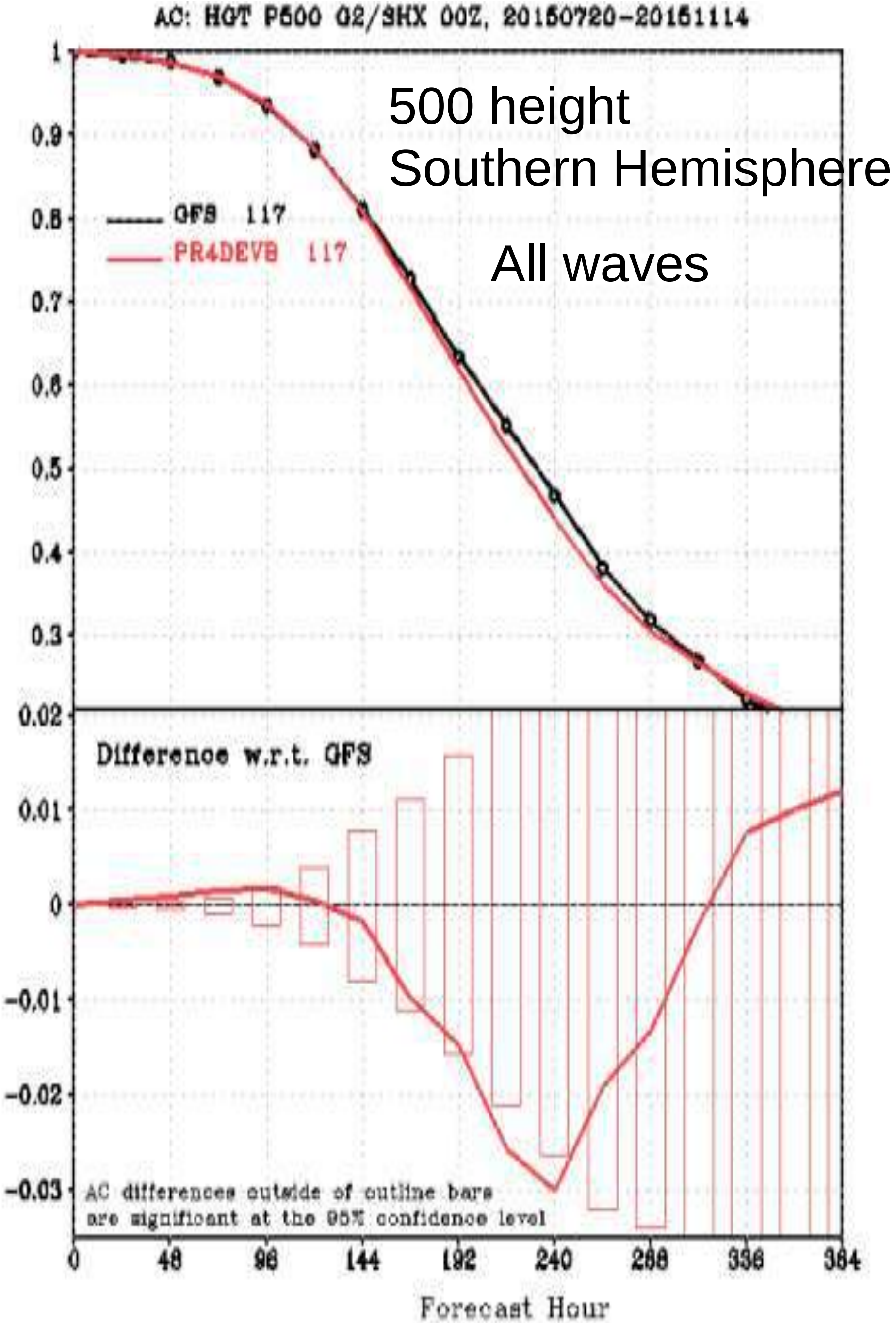
$$\frac{Z_{om}}{Z_{ot}} = \exp(k\, C \sqrt{R_e^*})$$

Re: roughness Reynolds number,
C: empirical constant; unknown in Zilitinkevich (1995) formulation,
Chen et al. (1997, BLM) suggested *C*=0.1, but can range from 0.01 to 1.0

Treatment of roughness length for heat and moisture was already implemented in 2010, here we focus tuning rsmin
Higher Ch will yield more evaporation but also sensible heat flux, but given the same amount of surface available energy plus nonlinear interaction between land and atmosphere, when LH increases, SH should decrease, and vice versa.


AC: HGT P500 G2/NHX 00Z, 20160720-20161114
500 height
Northern Hemisphere
All waves
GFS 117
PR4DEVB 117
Difference w.r.t. GFS
AC differences outside of outline bars
are significant at the 95% confidence level
Forecast Hour


AC: HGT_WV1/10-20 P500 G2/NHX 00Z, 20160720-20161114
Zonal waves 10-20
GFS 117
PR4DEVB 117
Against own analyses
Difference w.r.t. GFS
AC differences outside of outline bars
are significant at the 95% confidence level
Forecast Hour


AC: HGT P500 G2/SHX 00Z, 20150720-20151114
500 height
Southern Hemisphere
All waves
GFS 117
PR4DEVB 117
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AC differences outside of outline bars
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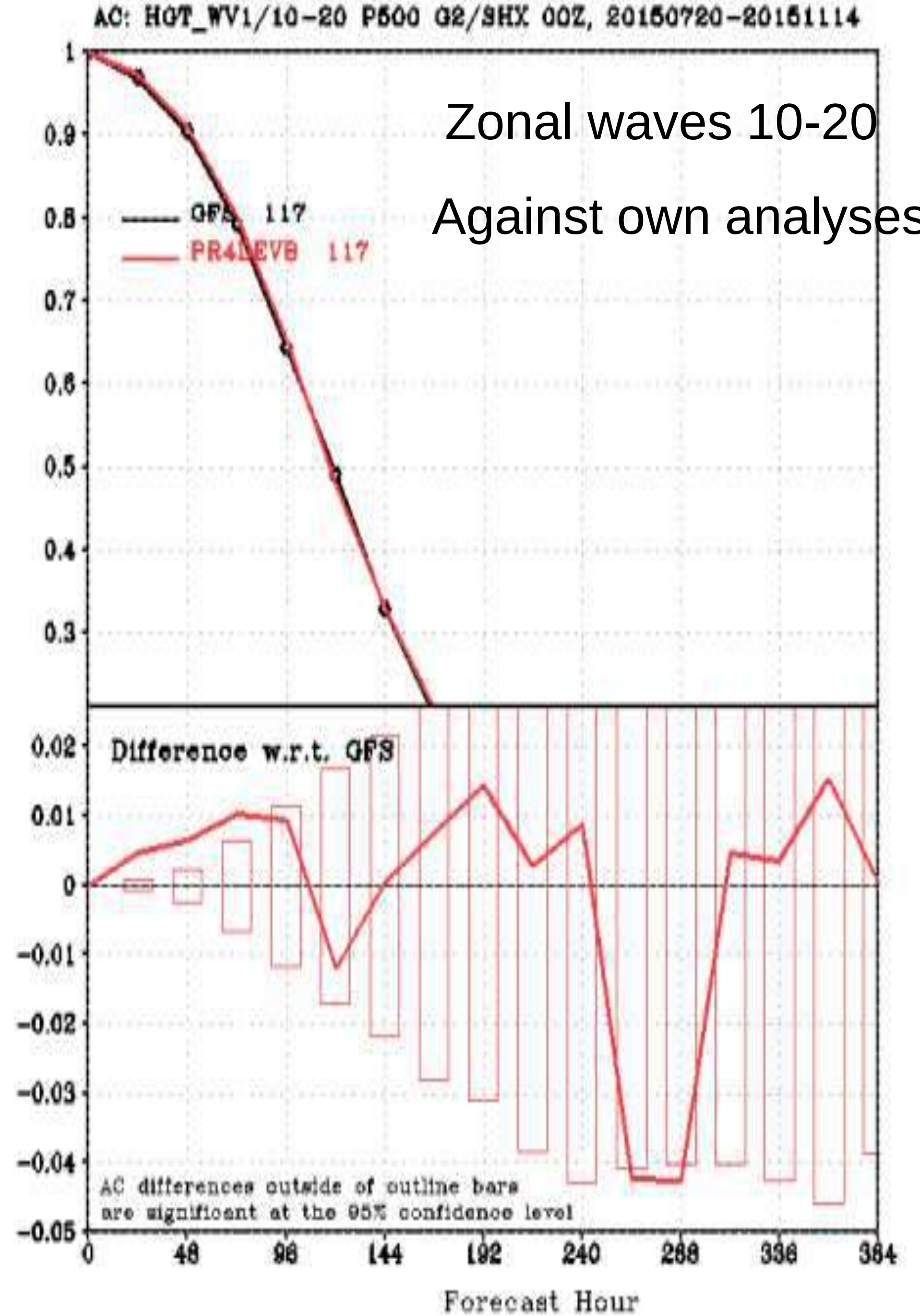
Forecast Hour


AC: HGT_WV1/10-20 P500 G2/SHX 00Z, 20150720-20151114
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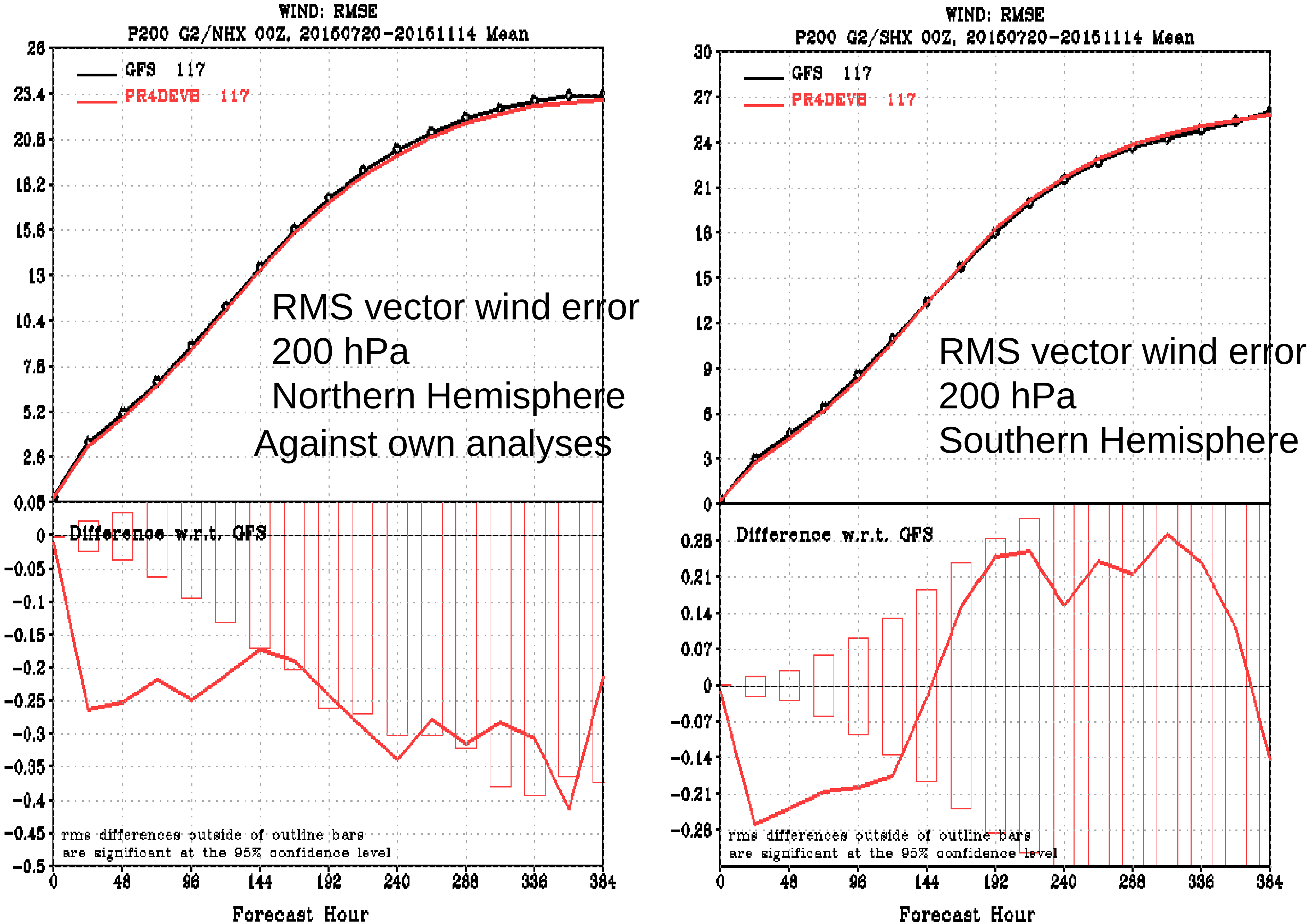
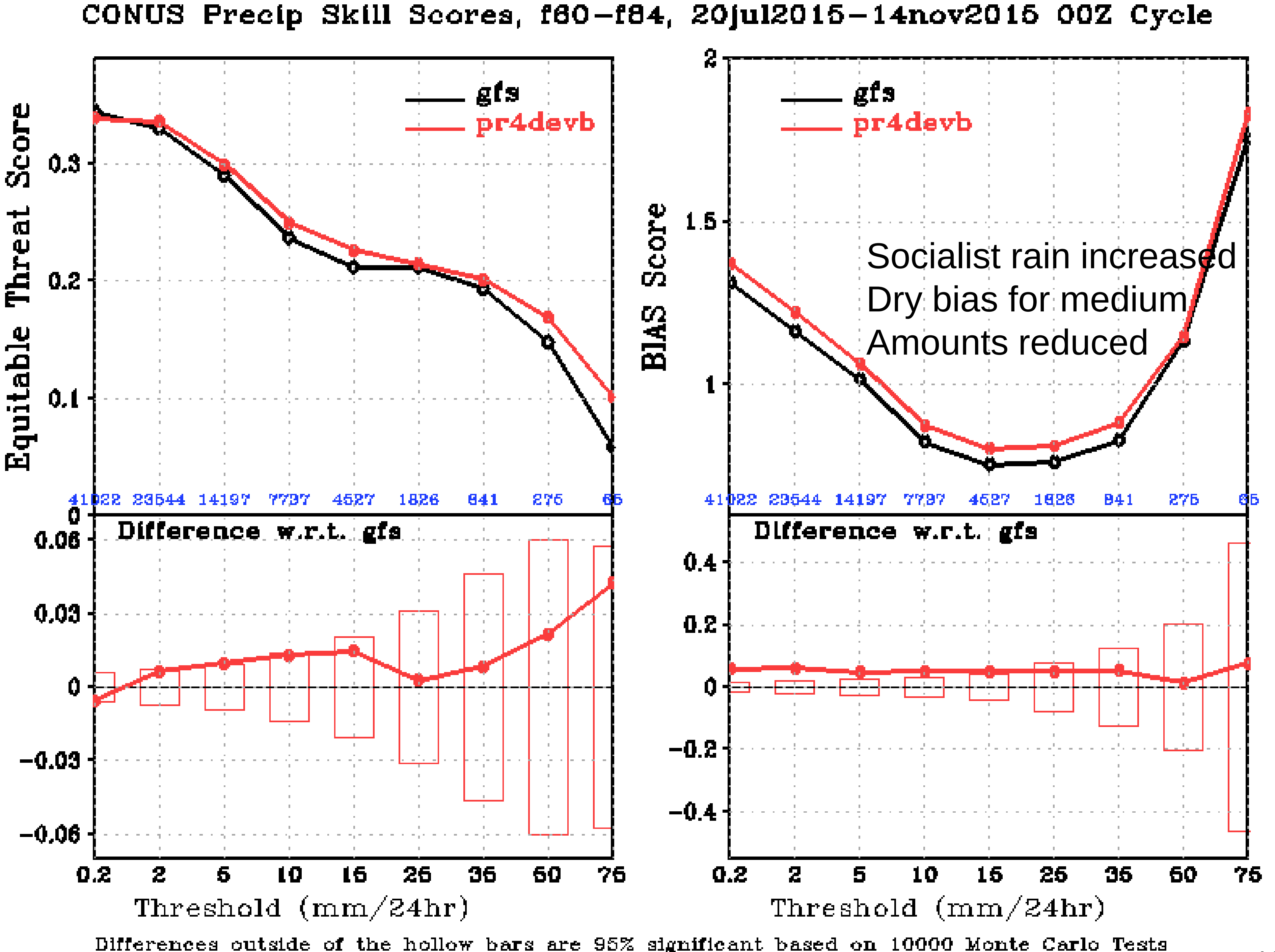
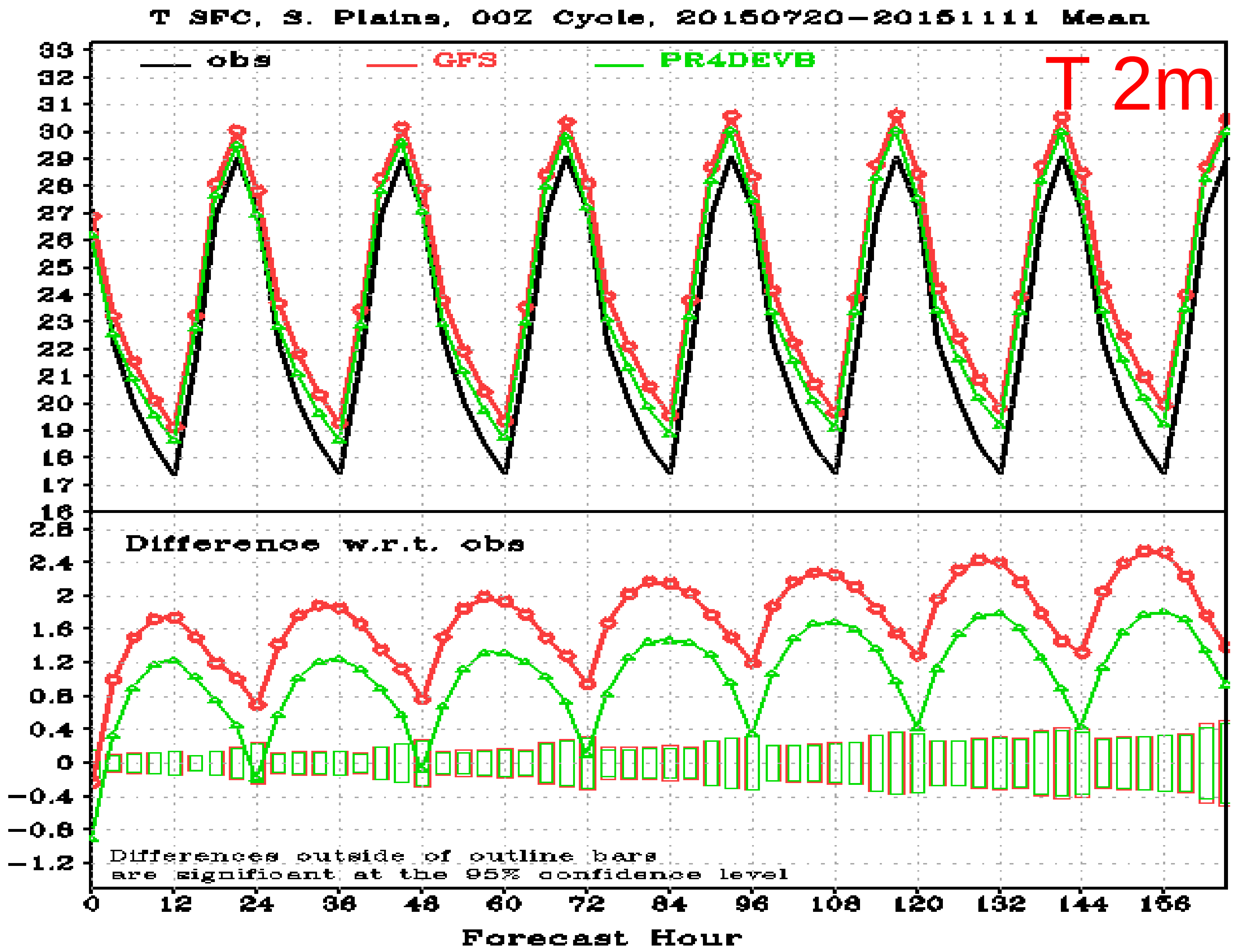
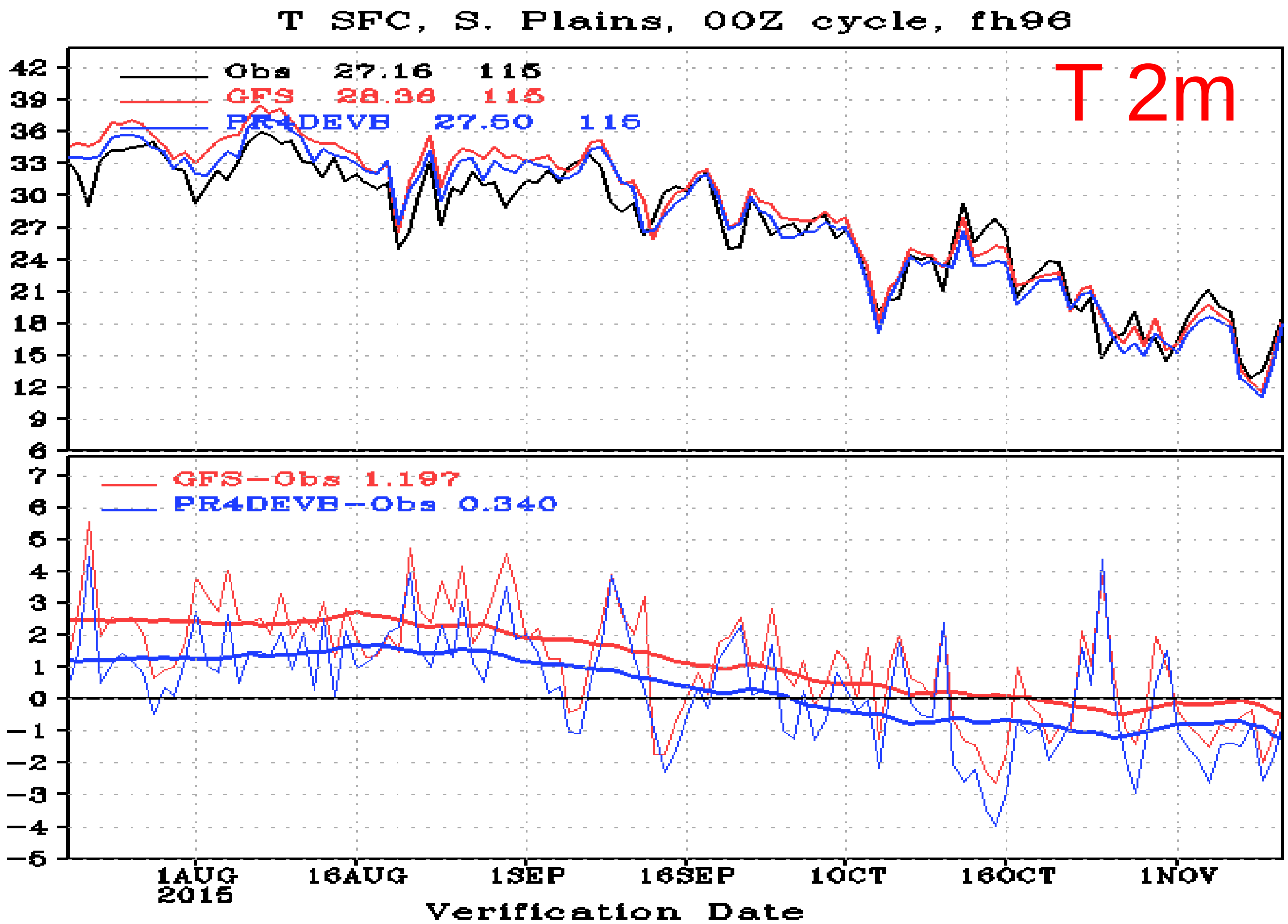
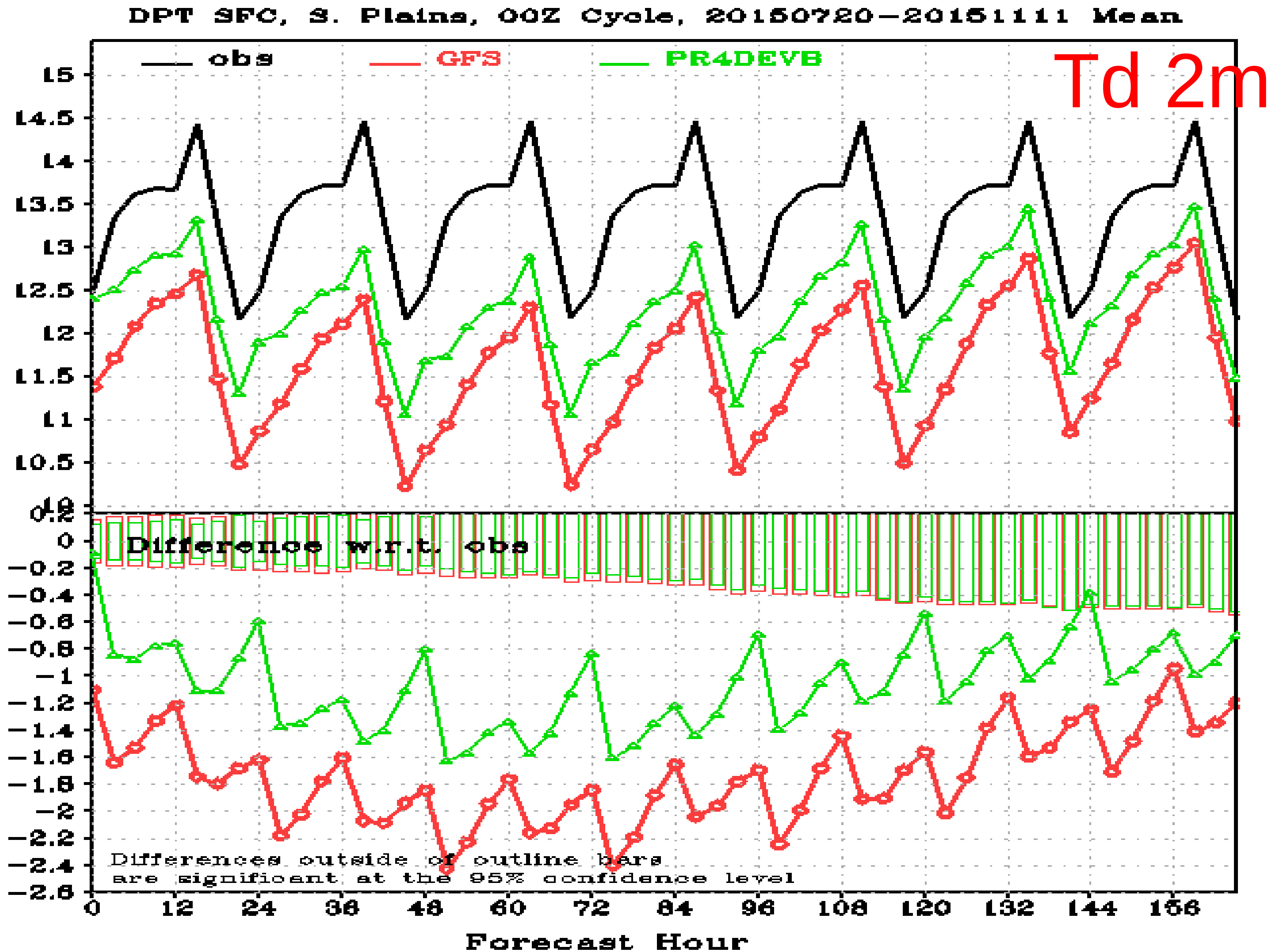

WIND: RMSE
P200 G2/NHX 00Z, 20160720-20161114 Mean
GFS 117
PR4DEVB 117
RMS vector wind error
200 hPa
Northern Hemisphere
Against own analyses
Difference w.r.t. GFS
rms differences outside of outline bars
are significant at the 95% confidence level
Forecast Hour
WIND: RMSE
P200 G2/SHX 00Z, 20160720-20161114 Mean
GFS 117
PR4DEVB 117
RMS vector wind error
200 hPa
Southern Hemisphere
Difference w.r.t. GFS
rms differences outside of outline bars
are significant at the 95% confidence level
Forecast Hour

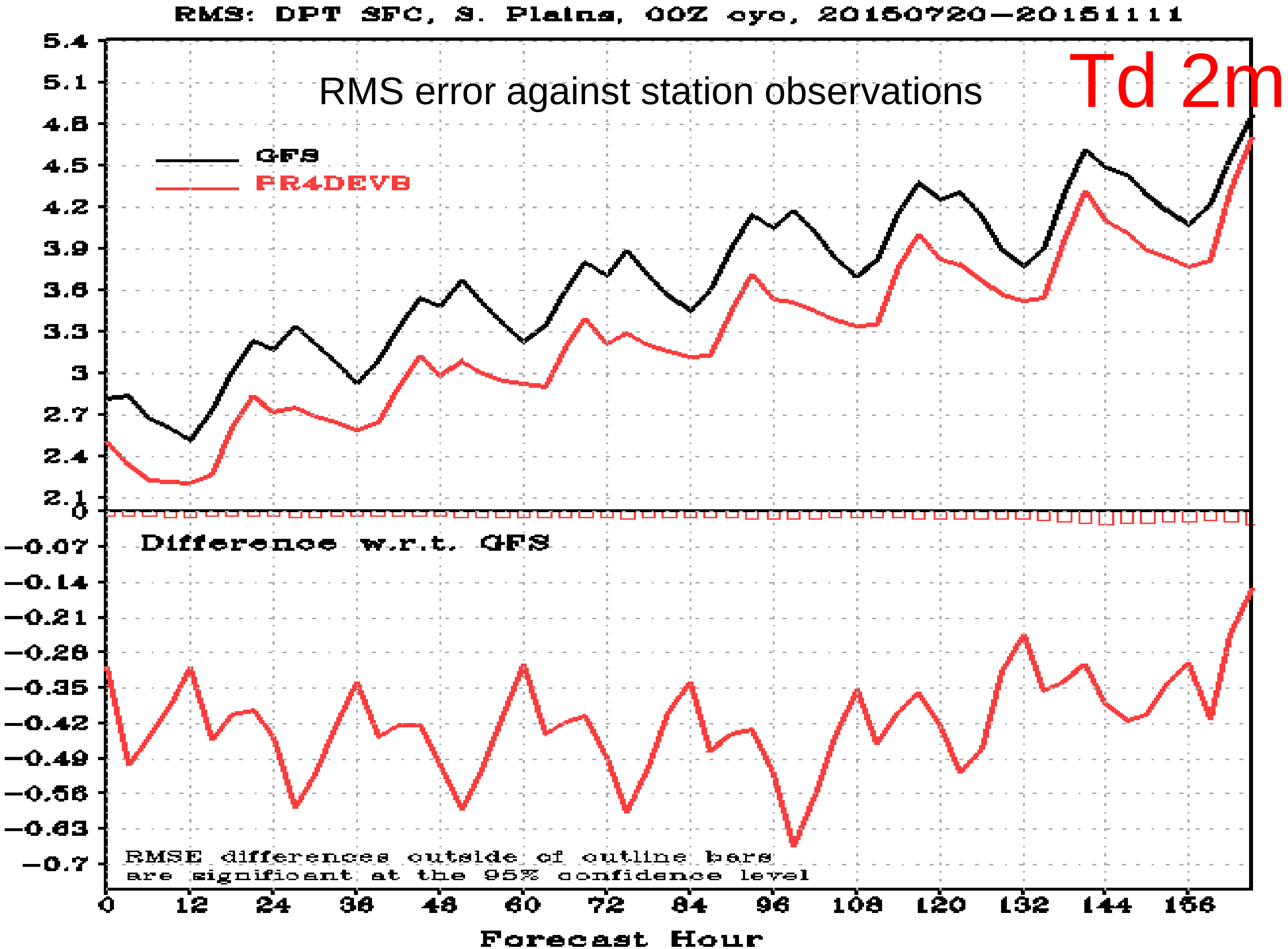


CONUS Precip Skill Scores, f60-f84, 20jul2015-14nov2015 00Z Cycle
Equitable Threat Score
BIAS Score
gfs
pr4devb
Socialist rain increased
Dry bias for medium
Amounts reduced
41022 23544 14197 7737 4527 1826 841 275 65
Difference w.r.t. gfs
Threshold (mm/24hr)
0.2 2 5 10 15 25 35 50 75
Differences outside of the hollow bars are 95% significant based on 10000 Monte Carlo Tests

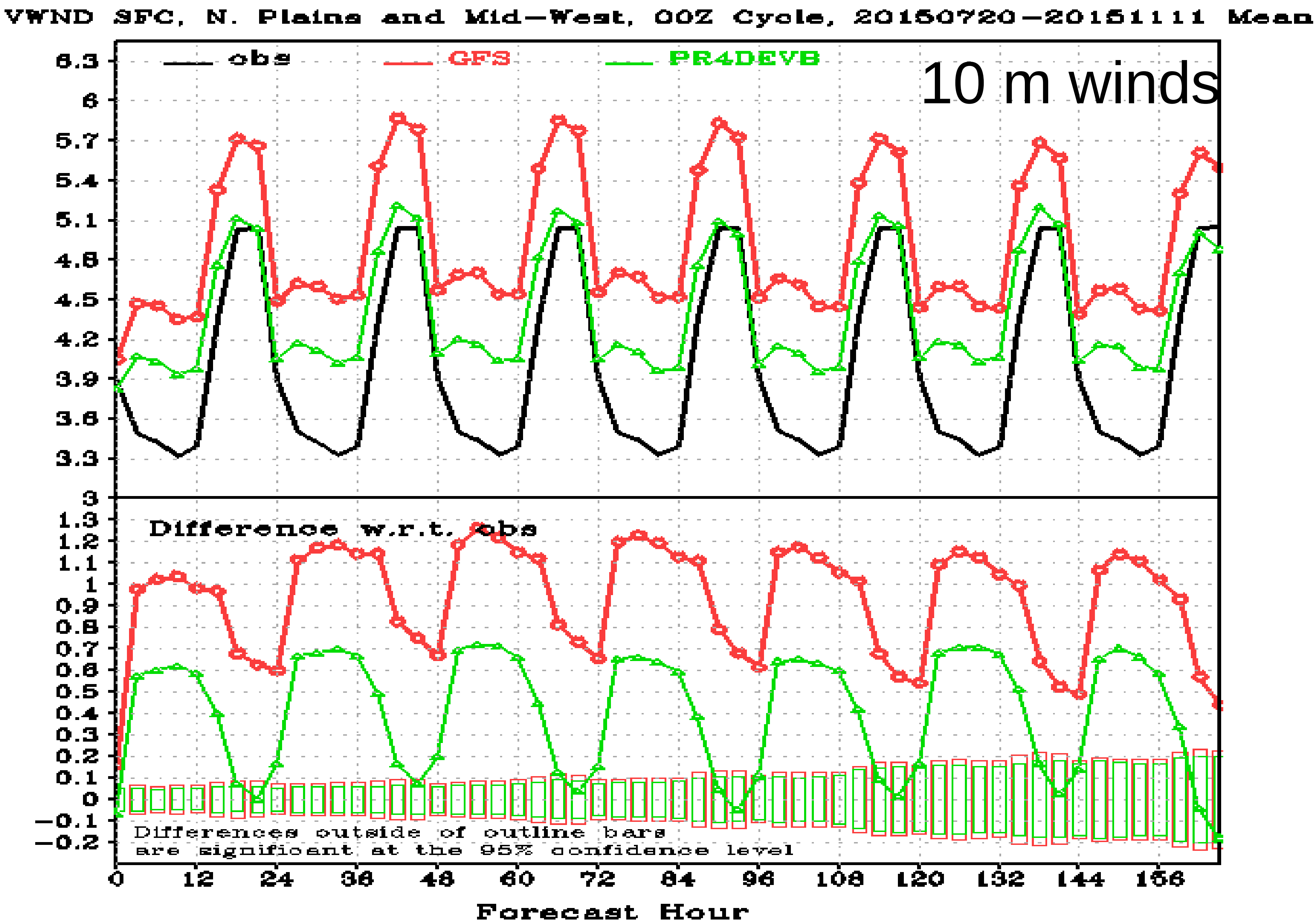

T SFC, S. Plains, 00Z Cycle, 20150720-20151111 Mean
obs
GFS
PR4DEVB
T 2m
Difference w.r.t. obs
Differences outside of outline bars
are significant at the 95% confidence level
Forecast Hour
0 12 24 36 48 60 72 84 96 108 120 132 144 156
33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16
2.8 2.4 2 1.6 1.2 0.8 0.4 0 −0.4 −0.8 −1.2


T SFC, S. Plains, 00Z cycle, fh96
T 2m
Obs 27.16 115
GFS 28.36 115
PR4DEVB 27.50 115
GFS–Obs 1.197
PR4DEVB–Obs 0.340
42
39
36
33
30
27
24
21
18
15
12
9
6
7
6
5
4
3
2
1
0
–1
–2
–3
–4
–5
1AUG 2015
16AUG
1SEP
16SEP
1OCT
16OCT
1NOV
Verification Date


DPT SFC, S. Plains, 00Z Cycle, 20150720–20151111 Mean
obs
GFS
PR4DEVB
Td 2m
Difference w.r.t. obs
Differences outside of outline bars
are significant at the 95% confidence level
Forecast Hour



RMS: DPT SFC, S. Plains, 00Z cyc, 20150720-20151111
RMS error against station observations
Td 2m
GFS
PR4DEVB
Difference w.r.t. GFS
RMSE differences outside of outline bars
are significant at the 95% confidence level
Forecast Hour

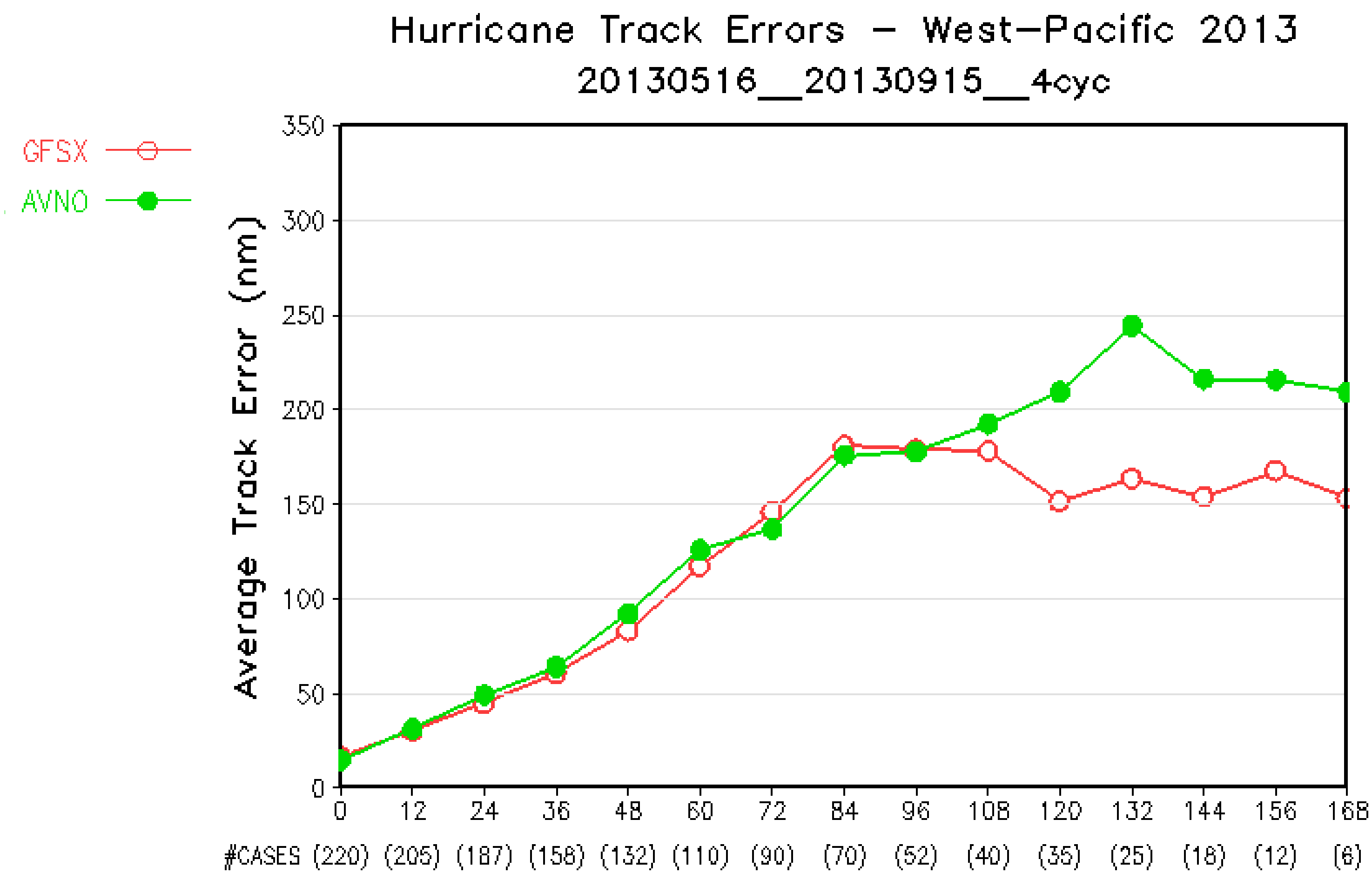

VWND SFC, N. Plains and Mid-West, 00Z Cycle, 20160720-20161111 Mean
obs
GFS
PR4DEVB
10 m winds
6.3
6
5.7
5.4
5.1
4.8
4.5
4.2
3.9
3.6
3.3
3
Difference w.r.t. obs
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
Differences outside of outline bars
are significant at the 95% confidence level
0
12
24
36
48
60
72
84
96
108
120
132
144
156
Forecast Hour

--huge, significant improvement in 2m T, 2m Td, 10 m winds over Great Plains, midwest, Southeast, both in bias and rms error against observations, some improvement Northeast

--little impact elsewhere in west, Alaska

--seasonal cycle in bias?

--whole diurnal cycle shifted, mistakes in diurnal cycle not addressed by this change


Hurricane Track Errors - West-Pacific 2013
20130516__20130915__4cyc
GFSX
AVNO
Average Track Error (nm)
0
50
100
150
200
250
300
350
0 12 24 36 48 60 72 84 96 108 120 132 144 156 168
#CASES (220) (205) (187) (158) (132) (110) (90) (70) (52) (40) (35) (25) (18) (12) (6)

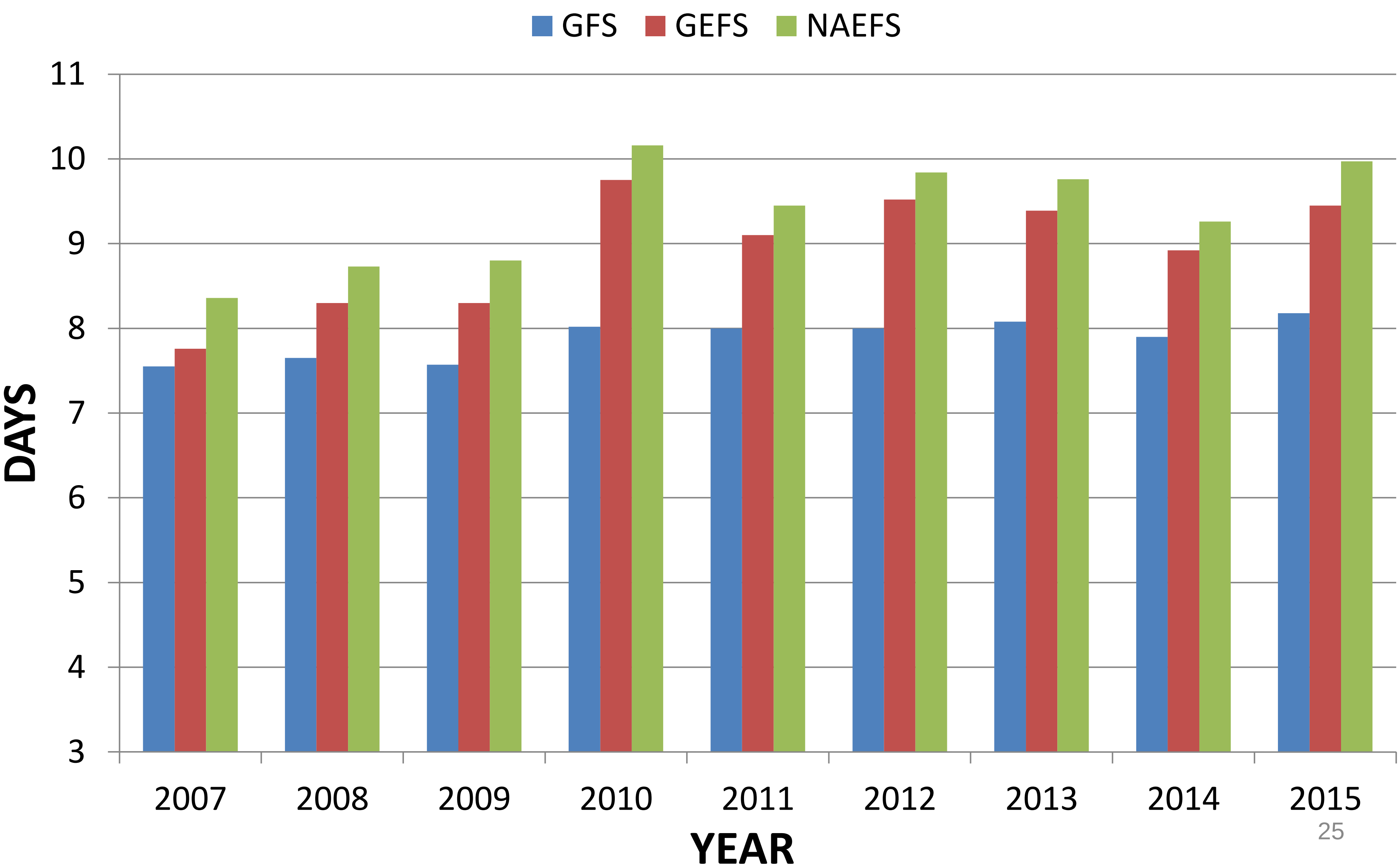
--hurricane tracks a concern—need days 6 and 7 and estimates of statistical significance

--forecasts of tropical cyclone genesis need to be assessed

--lot to assess—need to engage community

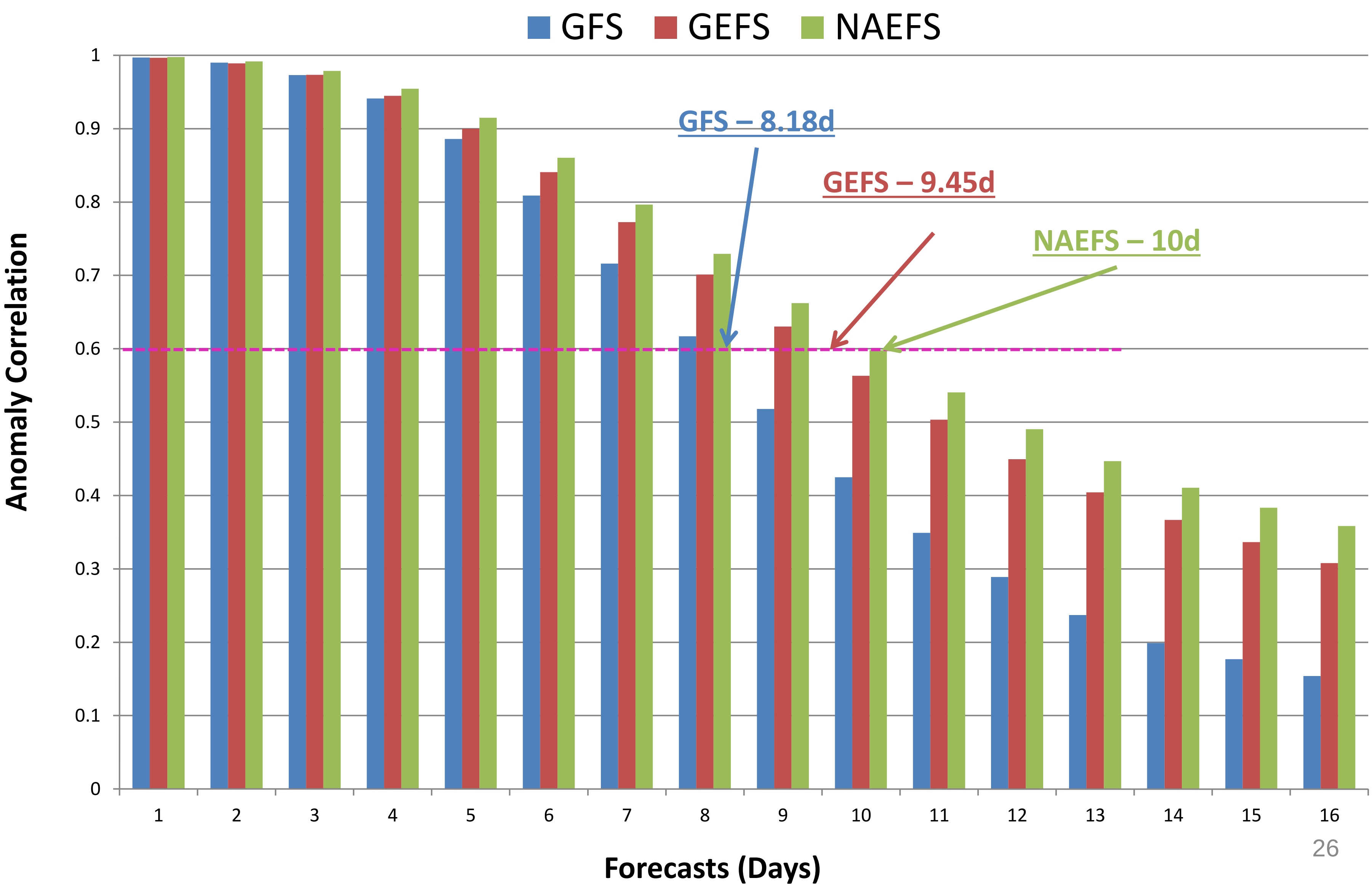
--new implementation process being introduced

Day at which forecast loses useful skill (AC=0.6)
N. Hemisphere 500hPa height calendar year means

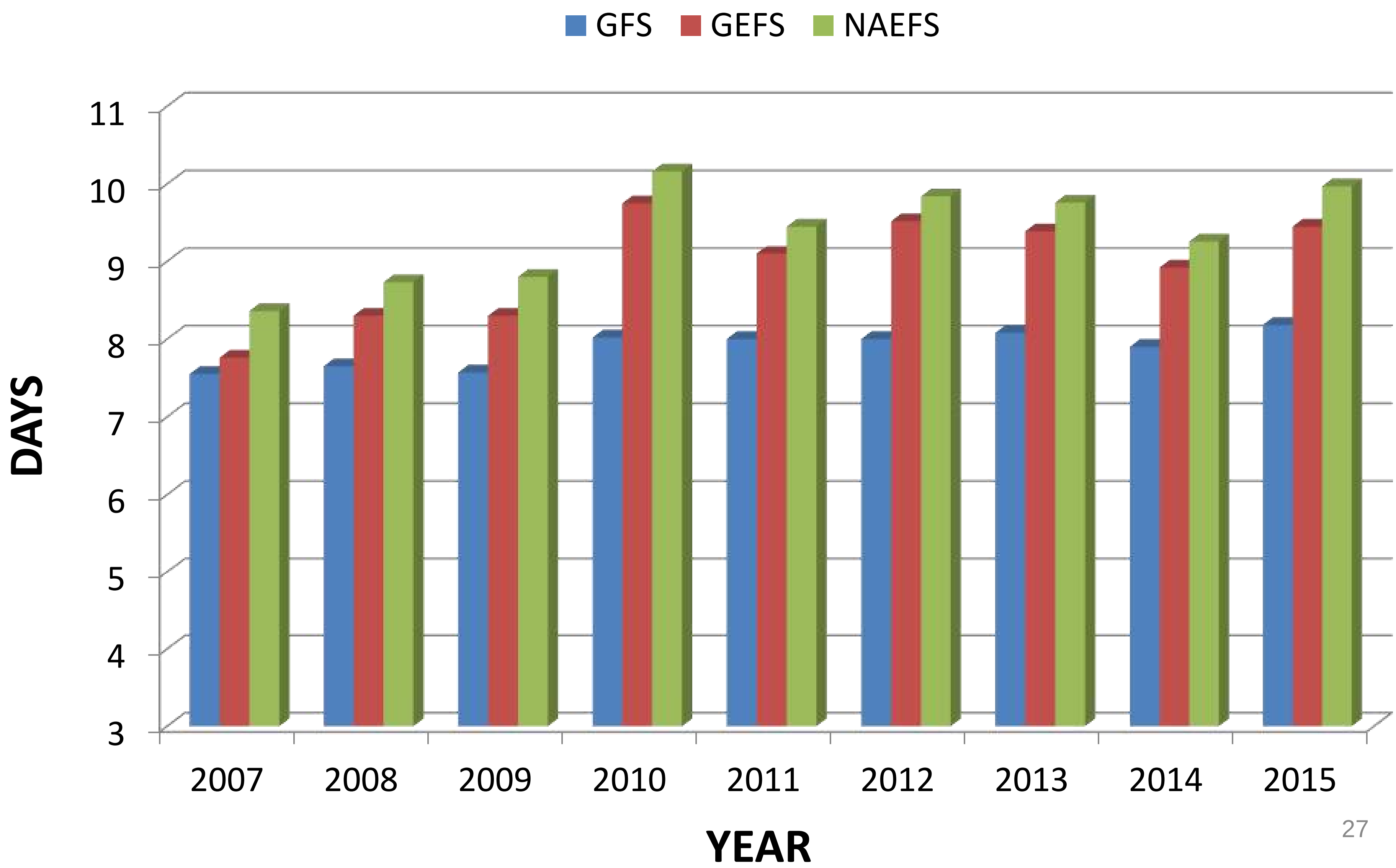


NH Anomaly Correlation for 500hPa Height

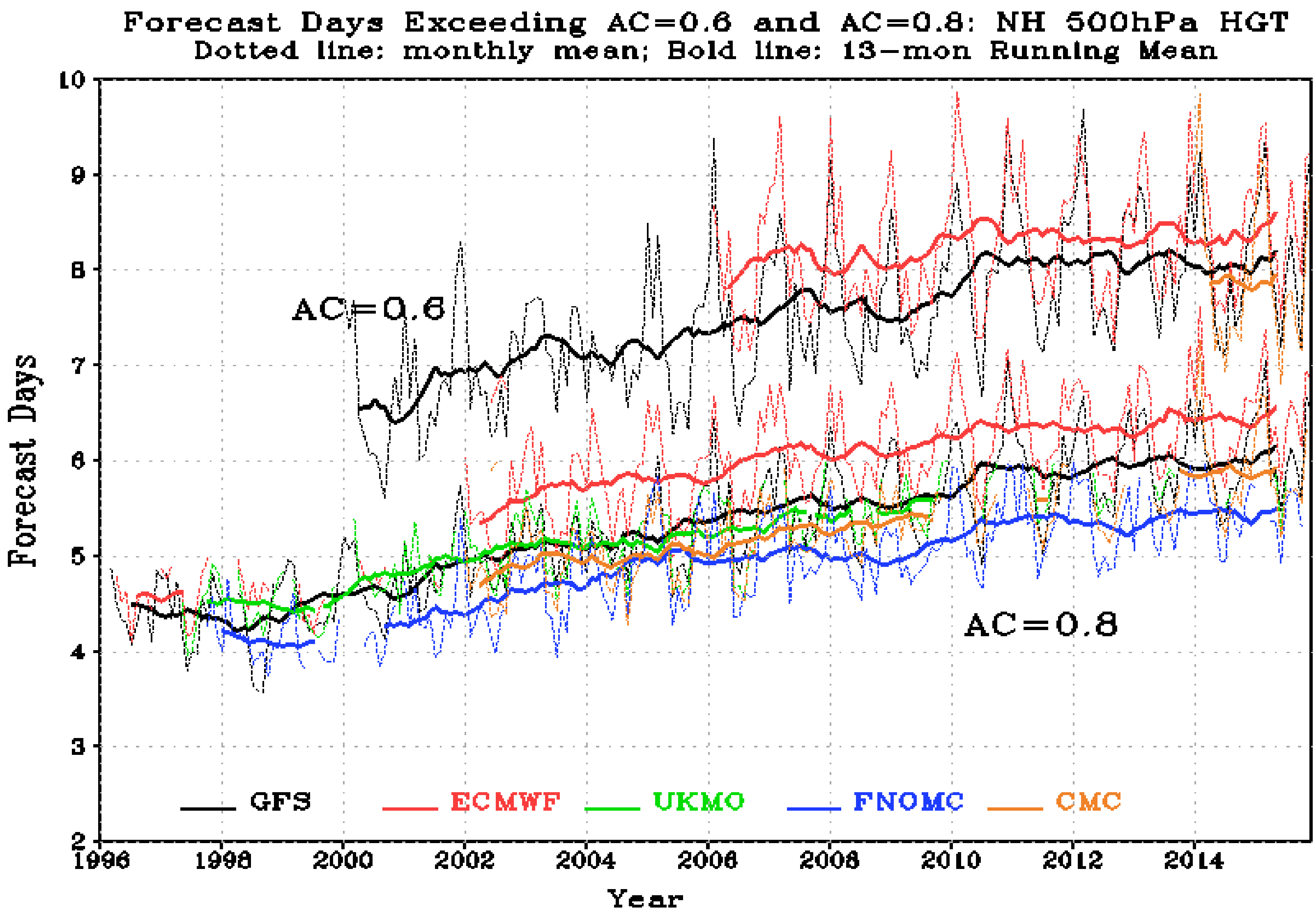
Period: January 1st – December 31st 2015



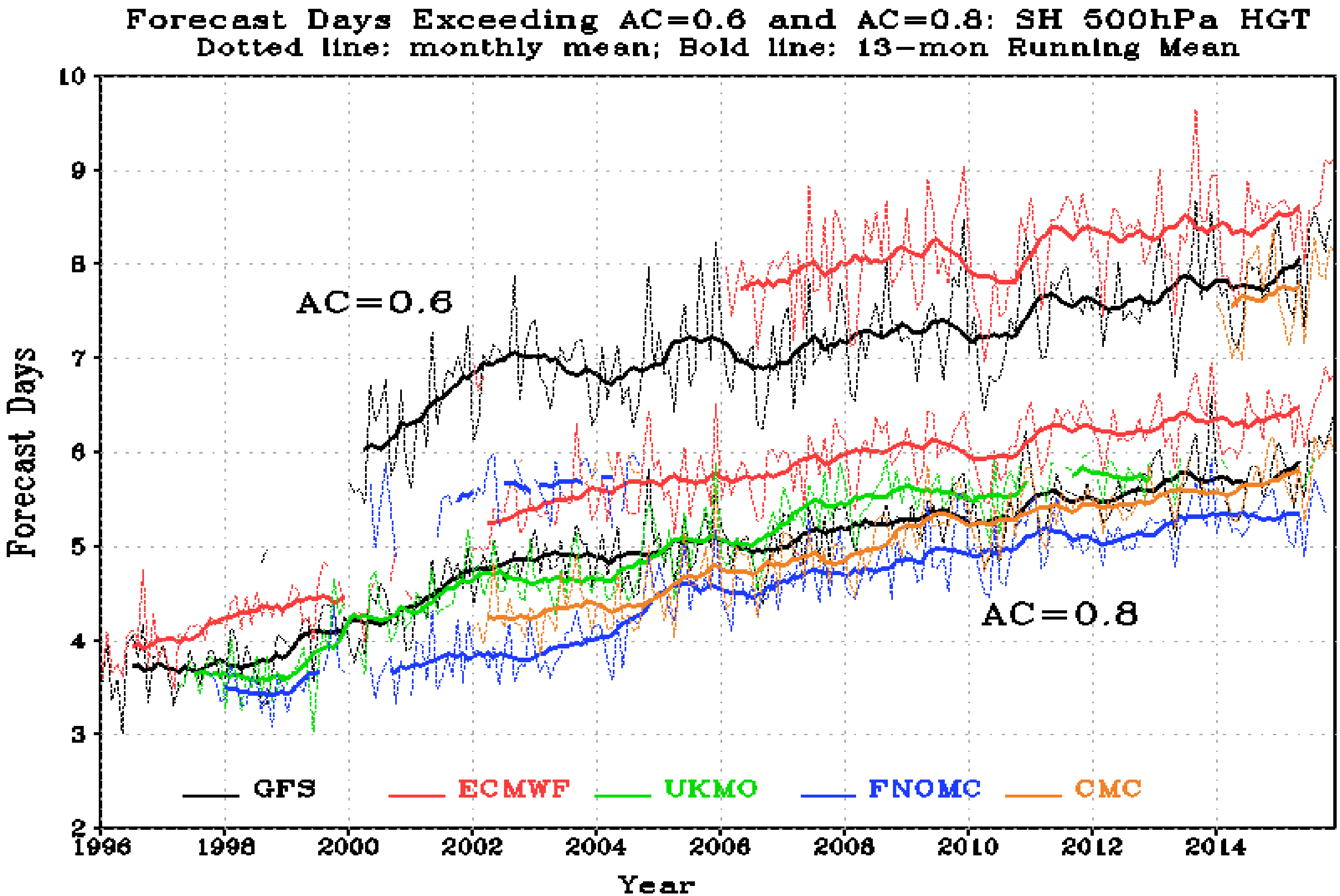
Day at which forecast loses useful skill (AC=0.6) N. Hemisphere 500hPa height calendar year means



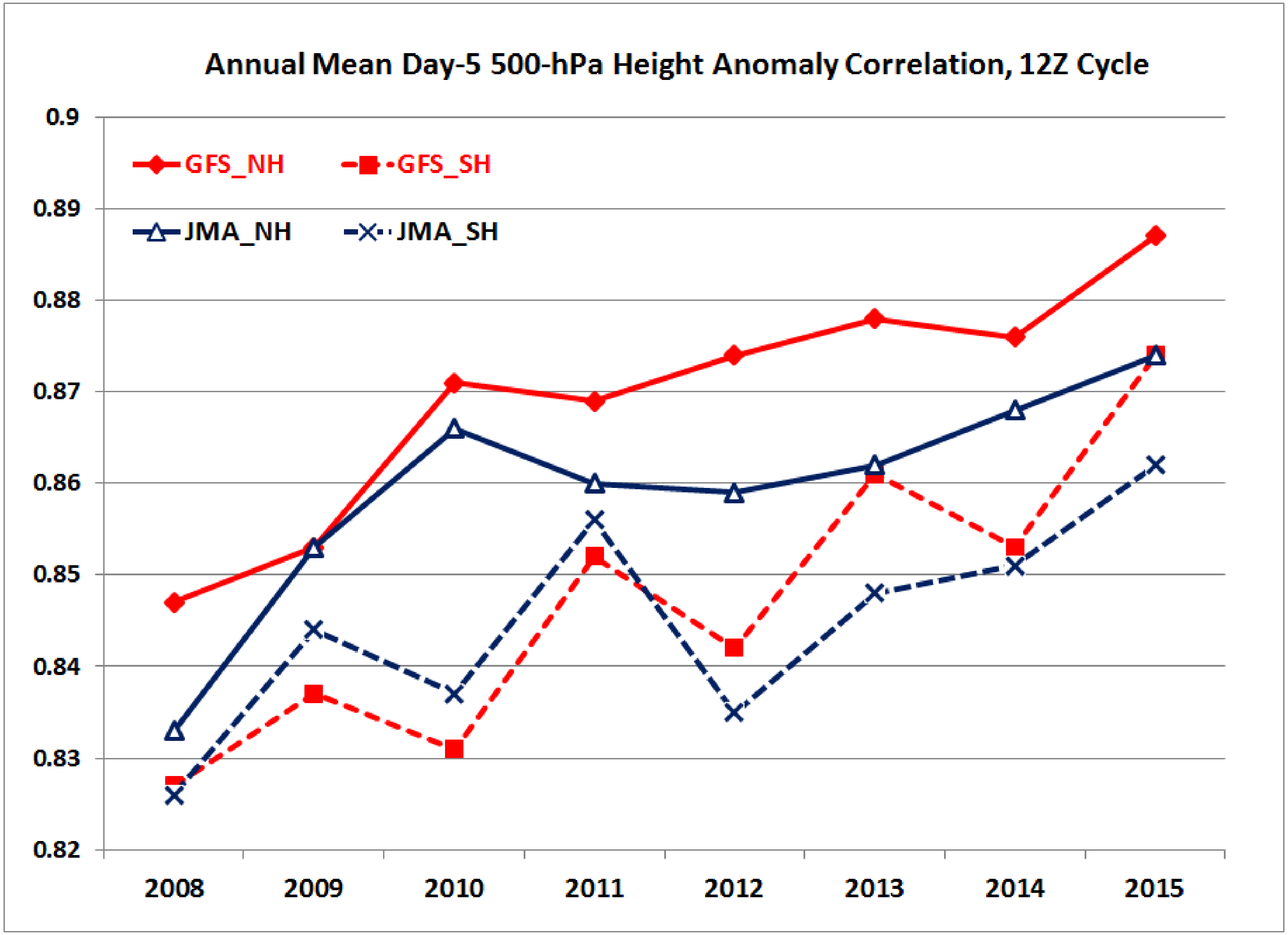
Day at which forecast loses useful skill Day at which forecast loses useful skill



Day at which forecast loses useful skill Day at which forecast loses useful skill



Historical Performance of GFS and JMA GSM



NOAA's Next Generation Global Prediction System:

Unified coupled modeling for seamless prediction of weather and climate

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NOAA / NWS / NCEP

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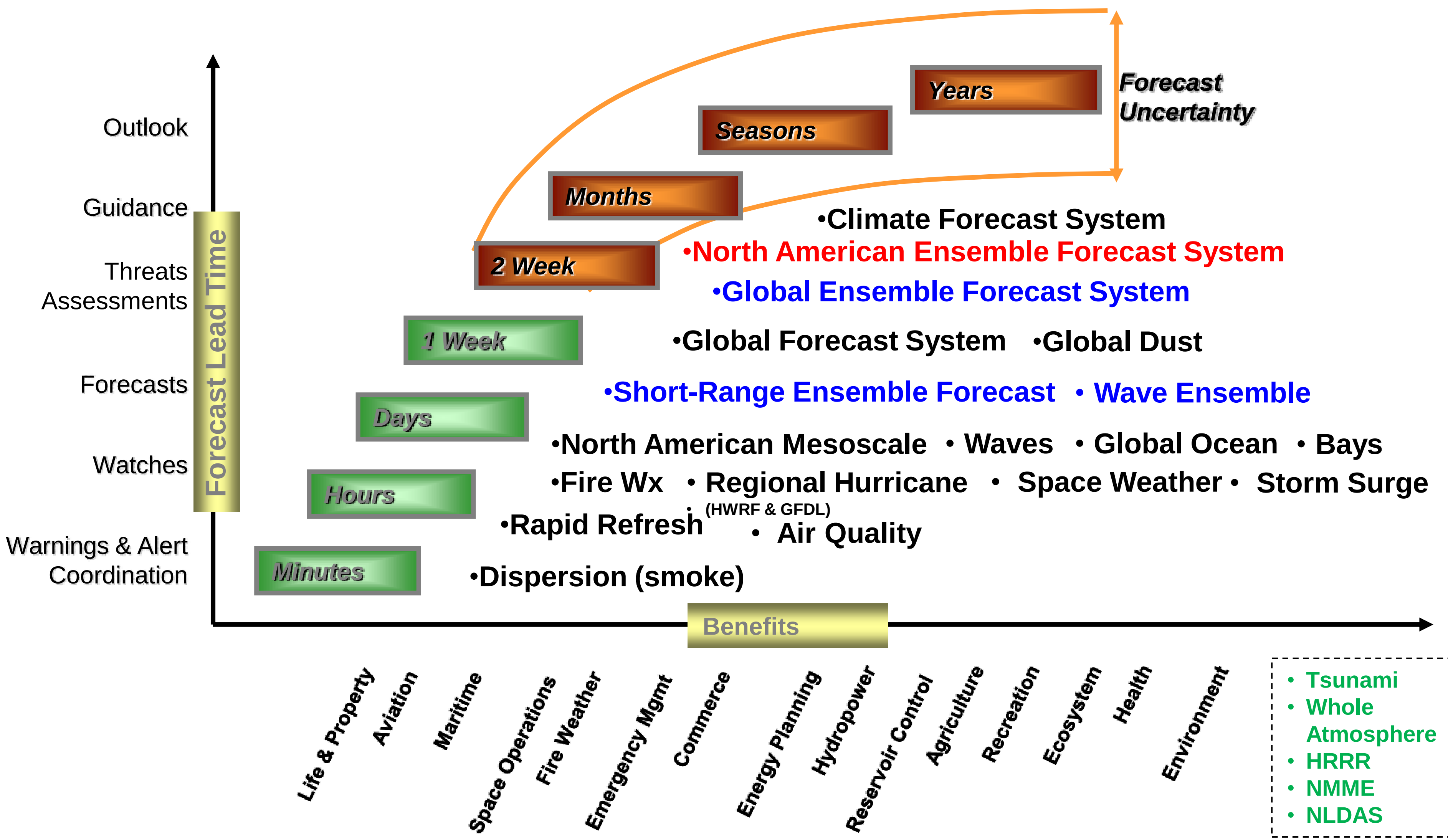
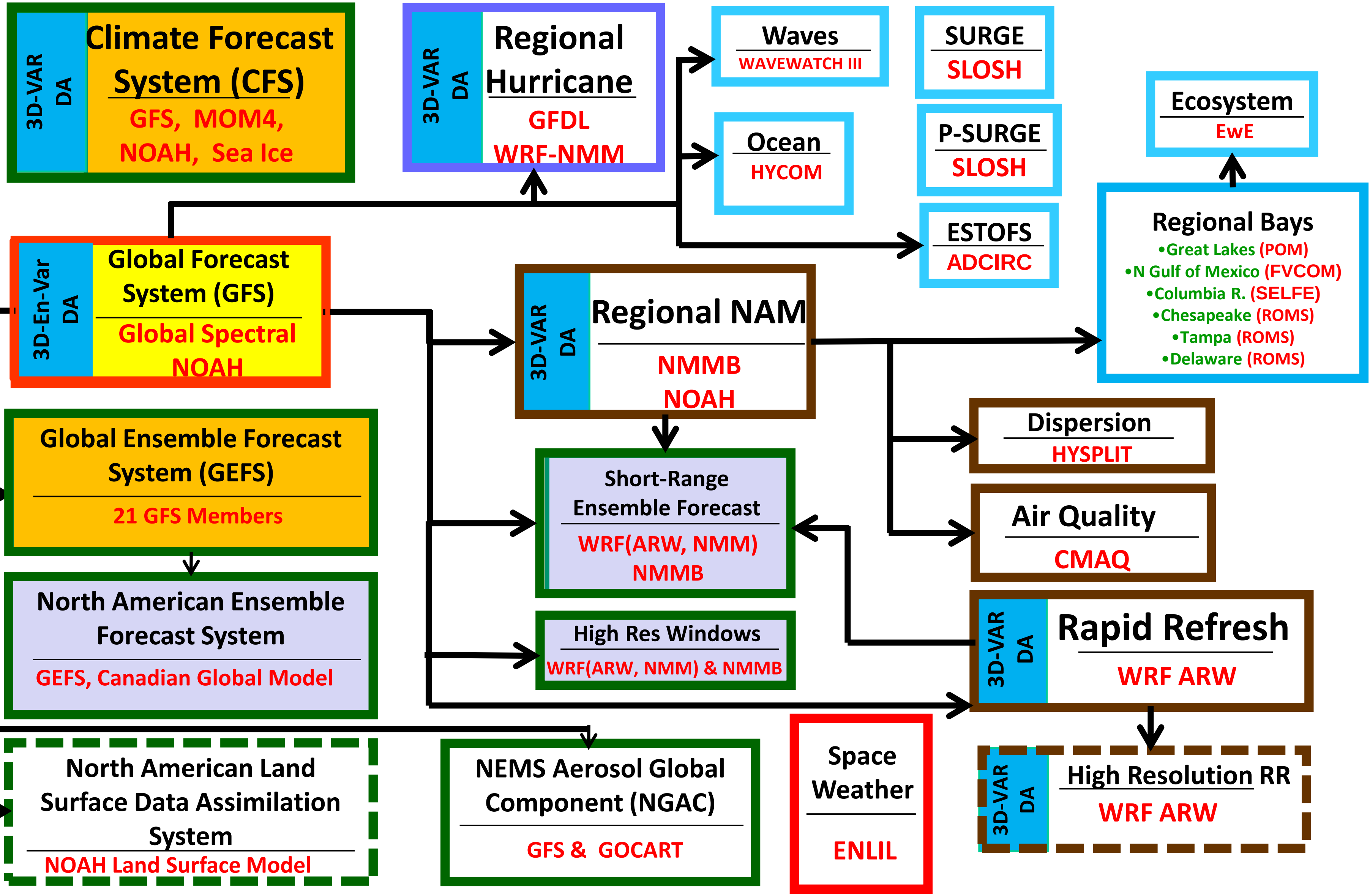
Contents

- The suite in 2 minutes
- Emerging requirements
- Forces driving unification of the model suite
  - UMAC (UCACN model advisory committee)
  - NGGPS (Next Generation Global Prediction System)

- What does this mean for our production suite?
  - High-level plans for simplified production suite
  - Unified Global Coupled Model
  - Dynamic cores
  - Physics
  - Data Assimilation

Seamless Suite, spanning weather and climate





Production suite ca. January 2014

Emerging requirements

- Weather Ready Nation.
  - Products.
  - Social science.
- High impact events.
- Weather to climate—seamless suite of guidance and products.
  - Week 3-4.
  - Systematic reforecast need.
    - Forecast uncertainty.
    - Calibration of outlook products.
- Range of products beyond weather:
  - Land, ice, ocean, waves, aerosols, (ecosystems, space weather).
  - Water cycle, National Water Center (NWC).

Future of Global Modeling at EMC

- NWS Initiative on developing Next Generation Global Prediction System
- **GOAL: Global Weather Prediction: Becoming Second to None**
- There are multiple ongoing efforts in developing non-hydrostatic dynamic cores for NCEP operations, both inside and outside the EMC global group.
- If we identify one that can meet our basic requirements, we will adopt it and evolve it to meet our full needs.
- A significant O2R2O process must then be implemented in order to make this effort an ultimate success.
- Two Phases of Testing for selection of new dycore for NGGPS

Production suite

- We have tended to *implement solutions* rather than *satisfy requirements*.
- Moving away from this:
  - Need better NWS requirements process.
  - Map requirements to products (not models).
  - Target model development better to requirements.
  - Business case is integral part of decisions.
    - Unified model with concentrated effort, versus
    - models tailored to selected requirements.
- Additional considerations
  - Coupled modeling needs to be considered in this context.
  - Focus on predictability and outlook products requires systematic ensemble / reanalysis (retrospective) / reforecast approach.

What could this mean for weather products ?

Range	Year	Month	Week	Day	Hour
Target	Seasonal outlook	S2S outlook	Medium range weather	Convection resolving	Warn On Forecast
Present models	CFS	"GEFS"	GFS / NAM / SREF / RAP / HWRF	HRRR / NAM nest / HiresW	none
Cadence	??? (is 6h)	6-24h (is 6h)	6h	1h	5-15m
Range	9-15 mo global	35-45d global	Up to 10d global (?)	18-24h regional	3h ? regional
Updates	4y	2y	1y	1y	1y
Reanalysis	1979-present	20-25y	3y	???	???
Where	???	WCOSS	WCOSS	WCOSS	???

- Ensemble based DA for all ranges (day and hour TBD).
- Unified global model with applications for ranges.
- Global / regional unification ?
- Target R&D resources to move here(critical science questions).
- Hurricanes & Space weather need to find place in layout.
- Map to requirements to set metrics.

Coupling

- This is not just a science problem
  - Requirements for additional, traditionally downstream products.
  - ‘”One-way” model coupling versus downstream model:
    - Increases forcing resolution of downstream models while
    - reducing I/O needed to force models.
    - Creates a better integrated test environment for holistic evaluation of model upgrades.
    - Less implementations.
    - Creates environment for investigating benefits of two-way coupling. Enables two-way coupling if science proves benefit.

- Negative aspects of coupling:
  - More complex modeling systems implementations.
  - Less flexibility to tailor products.

Coupling

- The table below identifies which of the potentially coupled model components already have products or in the production suite corresponding to the five forecast ranges.
  - Where no products exists, science may indicate benefit of coupling.
  - For the hourly forecast range, all still TBD.

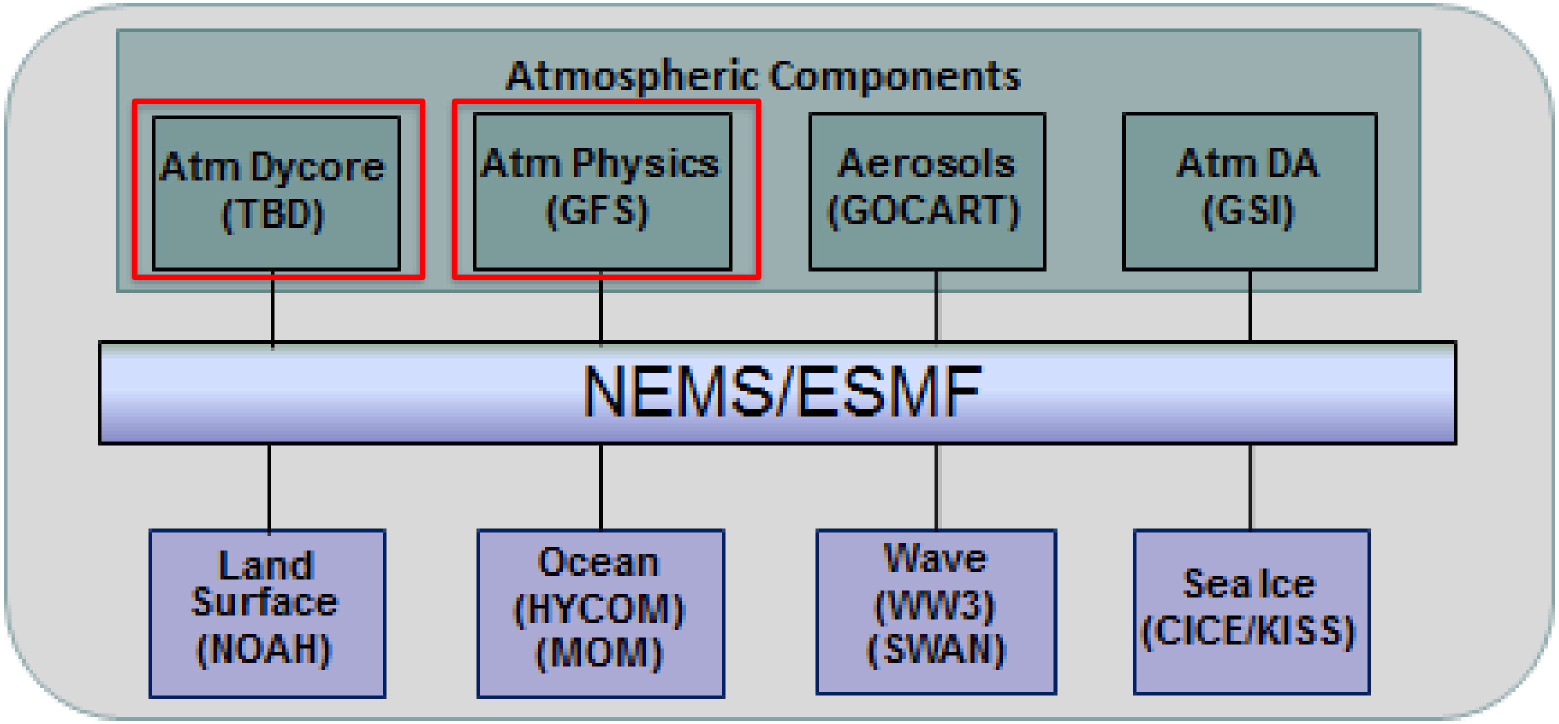
Subsystem	Year	Month	Week	Day	Hour
Land / hydro	Y	Y	Y	S	?
Ocean / coast	Y	Y	Y	S/R	?
Ice	Y	Y	S	?	?
Waves	S	Y	Y	Y	?
Aerosols	S	S	Y	Y	?

Y: present product
S: science benefit
R: unmet requirement
?: TBD

Back to NGGPS

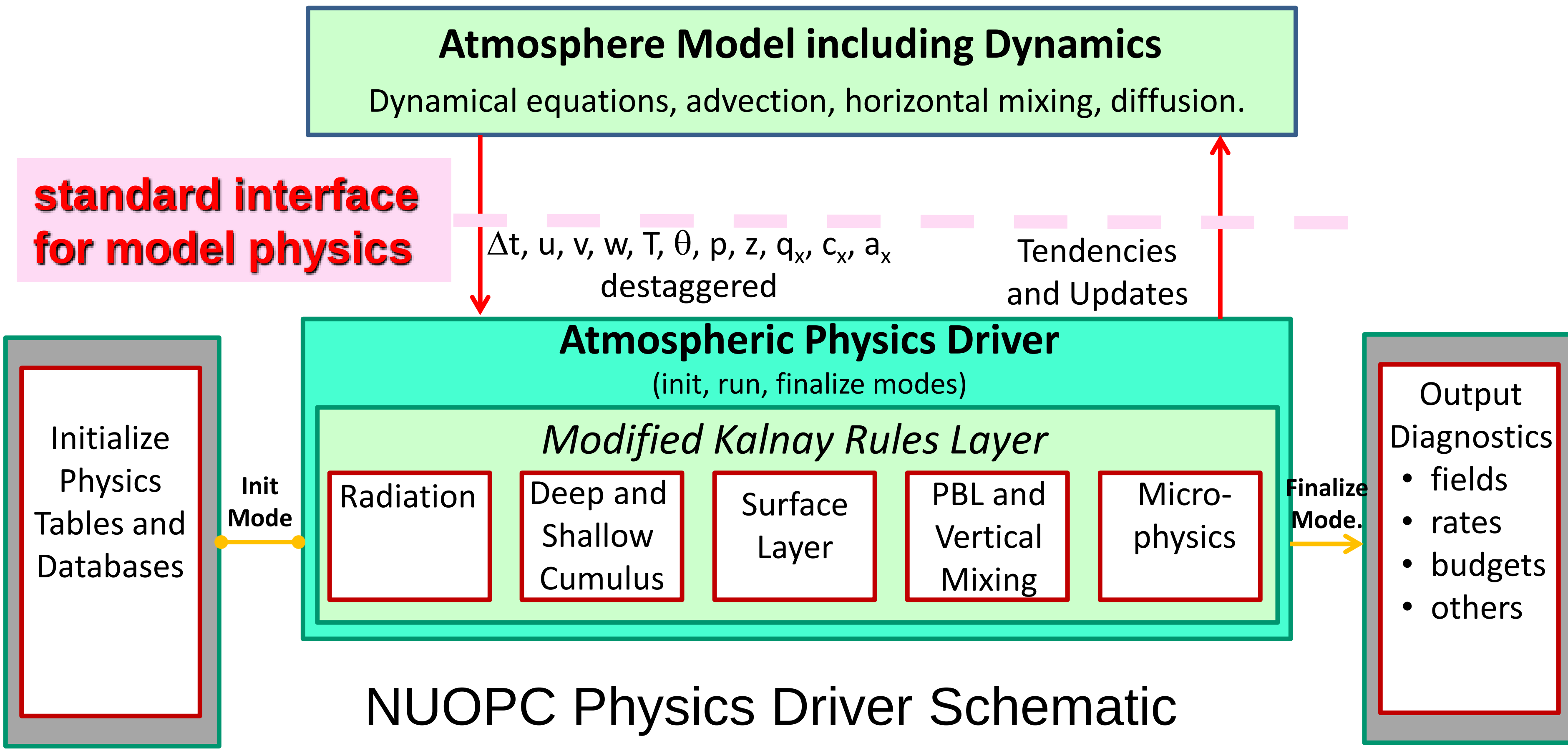
HOW TO GET THERE

NGGPS and NEMS / ESMF



Modular modeling, using ESMF to modularize elements in fully coupled unified global model
(+ *ionosphere , ecosystems , ……*)

NGGPS physics



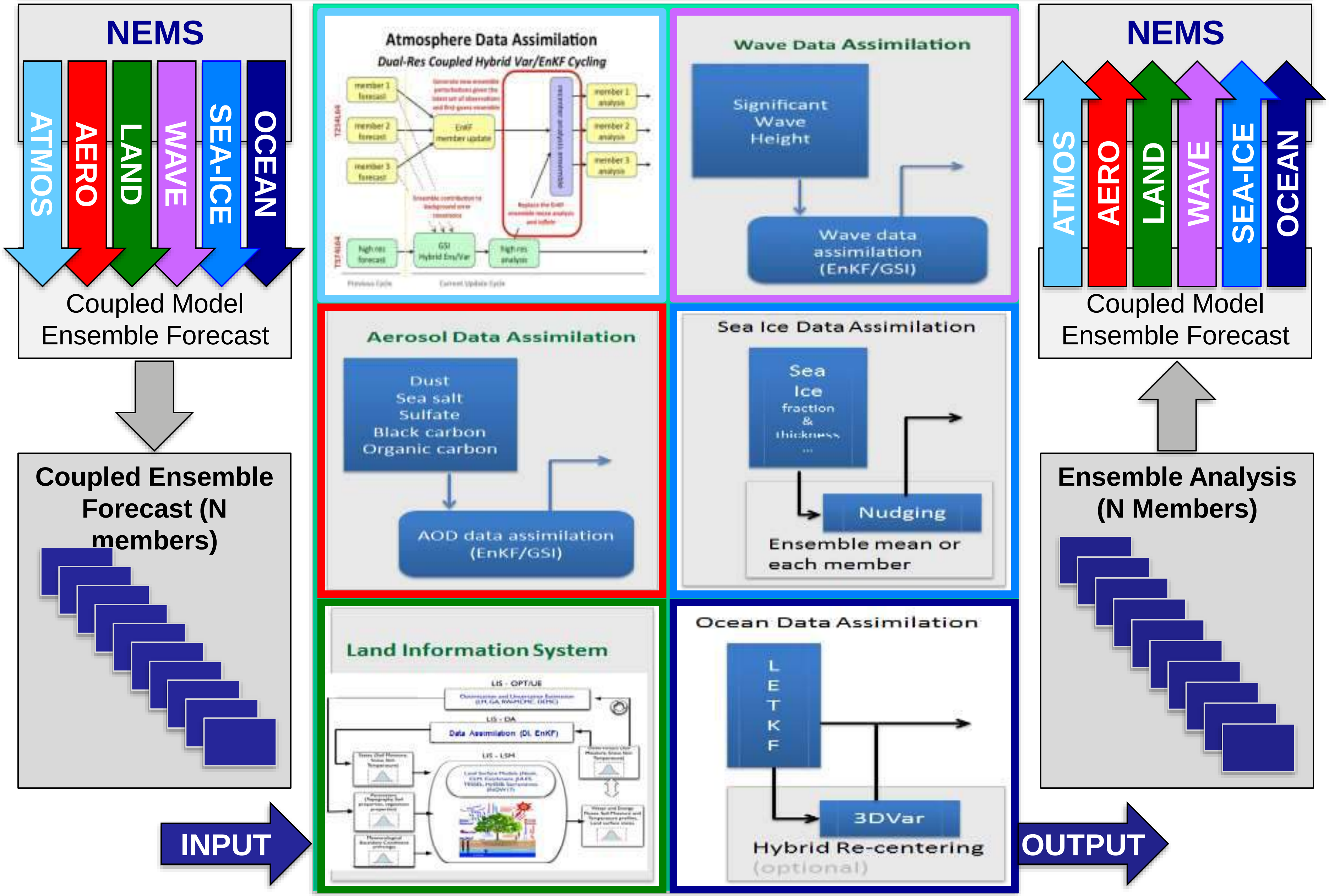
NUOPC Physics Driver Schematic

Version 1.0 delivered June 2015

COUPLED DA PROOF OF CONCEPT

- Atmosphere: Hybrid 4D-EnVAR approach using a 80-member coupled forecast and analysis ensemble, with Semi-lagrangian dynamics, and 128 levels in the vertical hybrid sigma/pressure coordinates.
- Ocean/Seaice: GFDL MOM5.1/MOM6-SIS and/or HYCOM-CICE for the ocean and sea-ice coupling, using the NEMS coupler.
- Aerosols: Inline GOCART for aerosol coupling.
- Waves: Inline WAVEWATCH III for wave coupling.
- Land: Inline Noah Land Model for land coupling.

NCEP Coupled Hybrid Data Assimilation and Forecast System



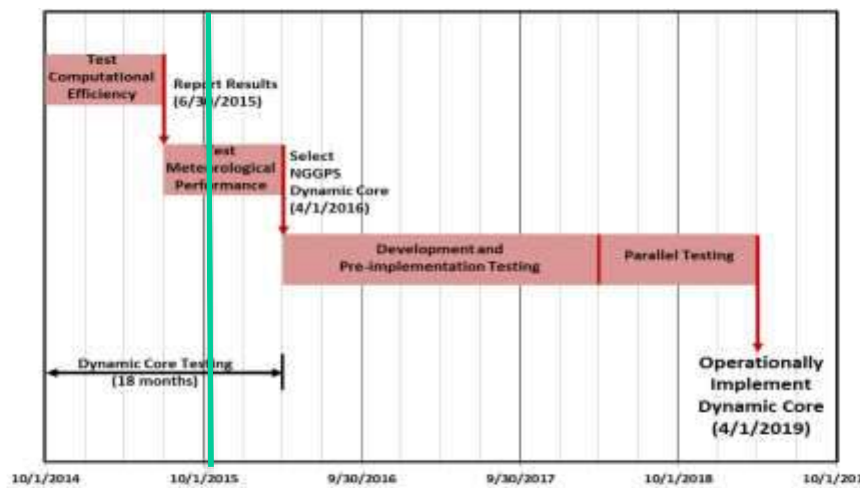
NGGPS Phase 1 Dycore Test Candidate Model Dynamic Cores

- FV3 (GFDL): Cubed-sphere finite-volume with flexible Lagrangian vertical coordinate (z or p base) with nesting or stretched grid capability
- MPAS (NCAR): Finite-volume C-grid staggering, icosahedral (z coordinate) with unstructured mesh refinement capability.
- NIM (ESRL): Icosahedral unstaggered A-grid mesh, finite-volume (z coordinate)
- NMM-UJ (EMC): Finite-difference, cubed-sphere version of Non-hydrostatic Mesoscale Model (p coordinate); Uniform Jacobian cubed sphere grid replaced lat/lon grid version with staggered B-grid (NMMB)
- NEPTUNE (Navy): Spectral-element (horizontal and vertical) cubed-sphere grid (z coordinate) with adaptive mesh refinement

Global Spectral Model not included – Non-hydrostatic version not available

NGGPS dycore

- Selecting a new dynamic core for global model to serve the NWS for the coming decades.
  - Architecture suitable for future compute environments.
  - Non-hydrostatic to allow for future convection-resolving global models.
- 18 month process to down-select candidate cores.
- 5 year plan to replace operations.
- Core → NEMS → applications.
  - ~~GSM-NH (EMC)~~
  - MPAS (NCAR)
  - FV3 (GFDL)
  - ~~NIM (ESRL)~~
  - ~~NEPTUNE (NRL)~~
  - ~~NMMB-UJ (EMC)~~

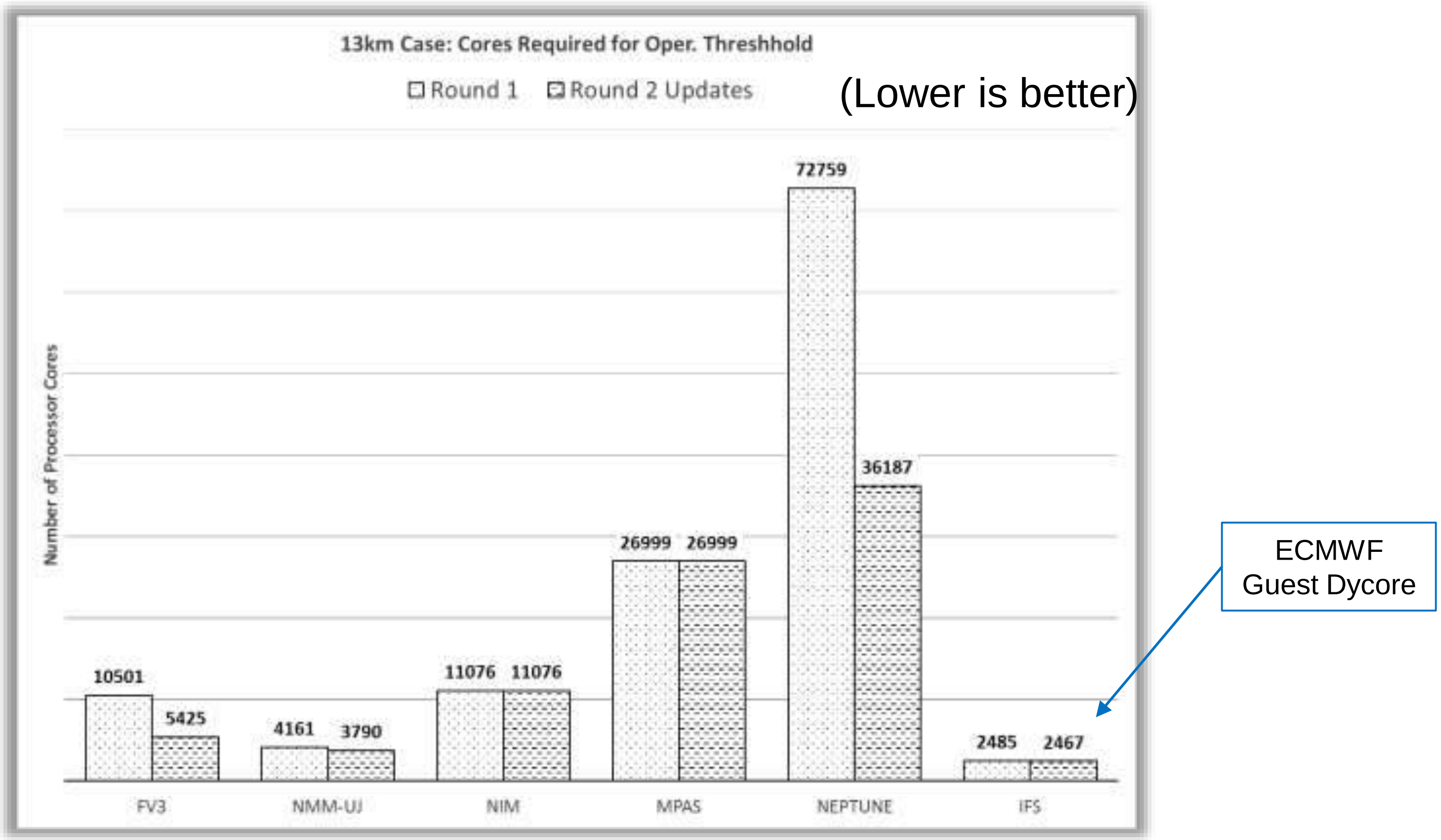


Phase 1 Dycore Testing Overview

Evaluation Criteria	How evaluation was done
Bit reproducibility for restart under identical conditions	Query model developers (AVEC)
Solution realism for dry adiabatic flows and simple moist convection	Perform series of idealized tests and evaluate solutions
High computational performance and scalability	Benchmarks run by AVEC
Extensible, well-documented software that is performance portable	Subjective evaluation of source code by AVEC
Execution and stability at high horizontal resolution (3 km or less) with realistic physics and orography	72-h forecasts with realistic physics and orography using operational GFS initial conditions (Moore tornado and Hurricane Sandy)
Lack of excessive grid imprinting	Evaluate idealized test case solutions

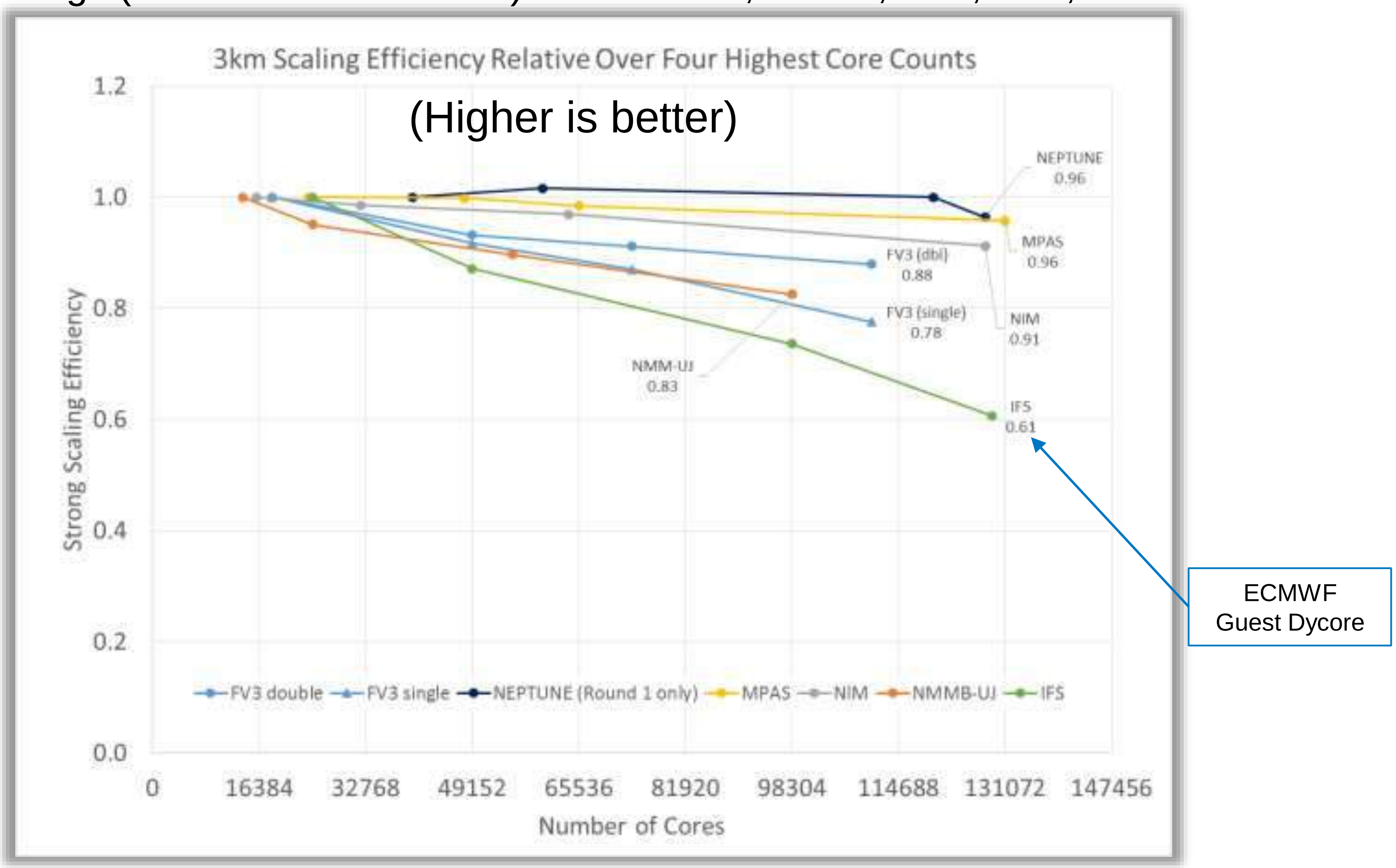
AVEC Phase 1 Evaluations: Performance

- Performance:
  - Number of processor cores needed to meet operational speed requirement with 13-km workload
  - Rankings (fastest to slowest): NMM-UJ, FV3, NIM, MPAS, NEPTUNE



AVEC Phase 1 Evaluations: Scalability

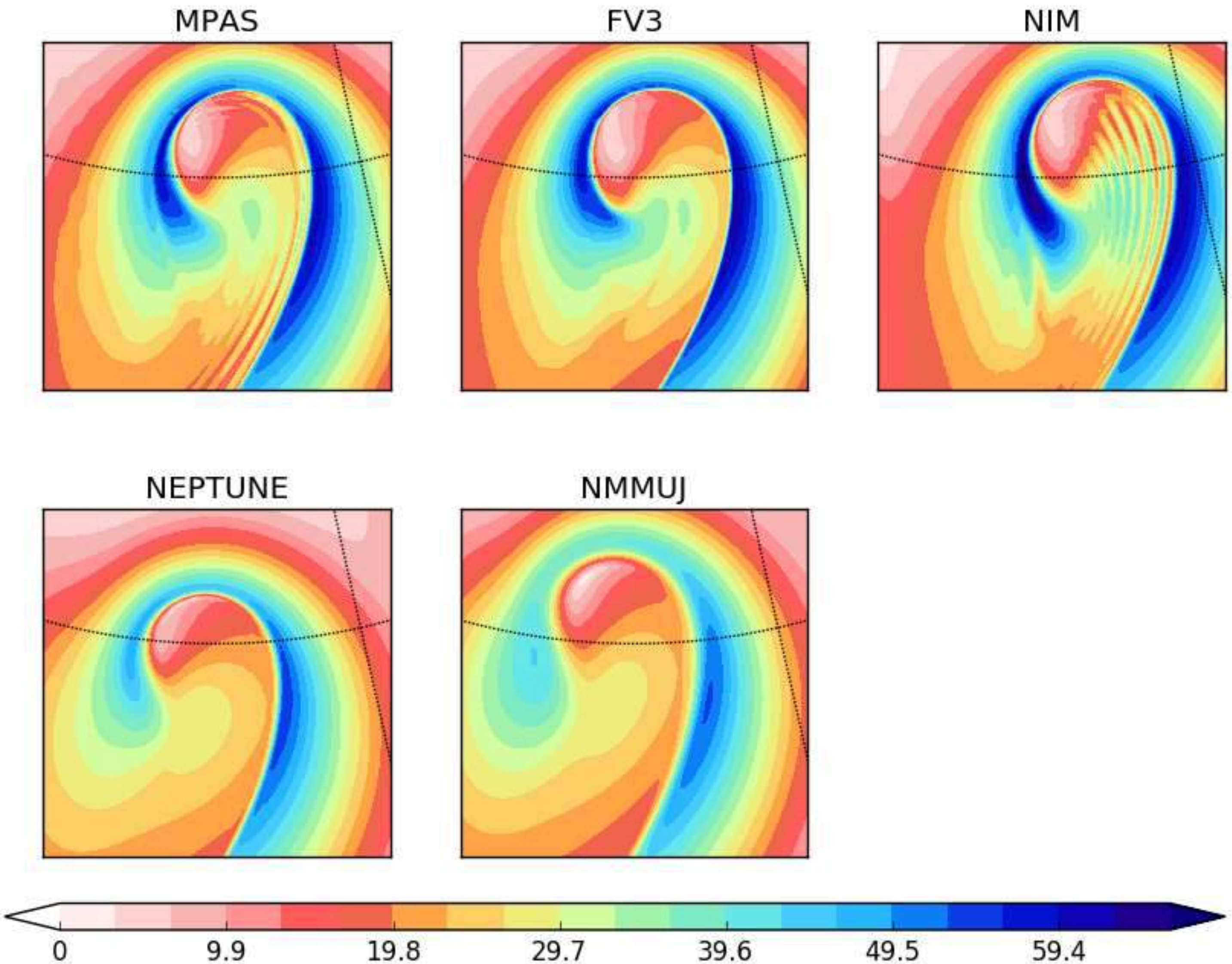
- Scalability: ability to efficiently use large numbers of processor cores
  - All codes showed good scaling
  - Rankings (most to least scalable): NEPTUNE, MPAS, NIM, FV3, NMM-UJ



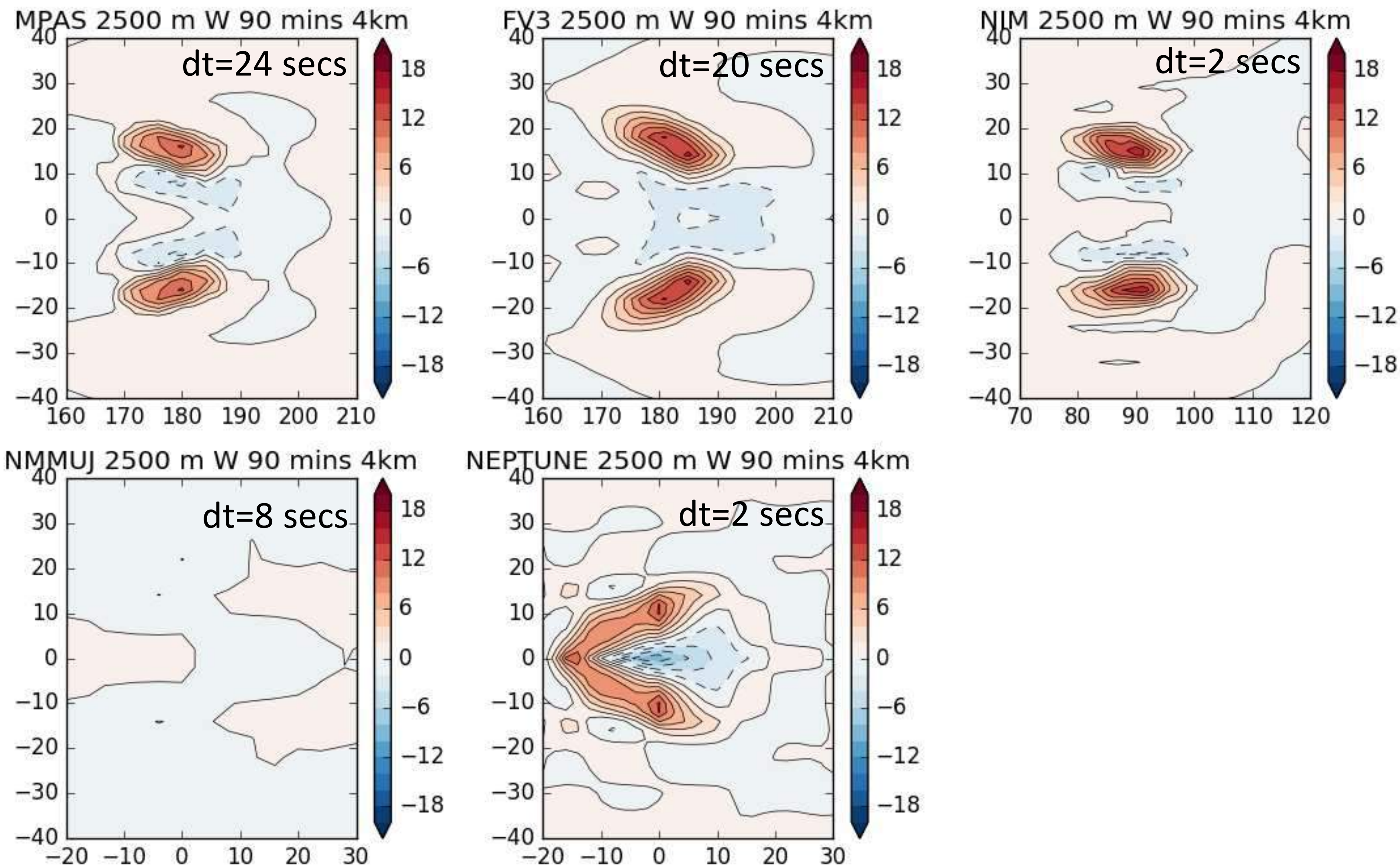
Idealized Tests

- ***Baroclinic wave test with embedded fronts*** (DCMIP 4.1)
  - Dynamics strongly forces solution to shortest resolvable scales
  - Shows impact of truncation error near quasi-singular points on computational grid (“grid imprinting”)
  - 15/30/60/120 km horizontal resolutions with 30 and 60 vertical levels
- ***Non-hydrostatic mountain waves on a reduced-radius sphere*** (like DCMIP 2.1/2.2)
  - Shows ability to simulate non-hydrostatic gravity waves excited by flow over orography
  - 3 tests: M1 (uniform flow over a ridge-like mountain), M2 (uniform flow over circular mountain), M3 (vertically sheared flow over a circular mountain). Solutions are all quasi-linear
- ***Idealized supercell thunderstorm on a reduced-radius sphere***
  - Convection is initiated with a warm bubble in a convectively unstable sounding in vertical shear
  - Simple Kessler warm-rain microphysics, free-slip lower boundary (no boundary layer)
  - Splitting supercell storms result after 1-2 hours of integration
  - 0.5/1/2/4 km horizontal resolutions

Baroclinic Wave (Sfc Wind Speed at Day 9, 15-km resolution)



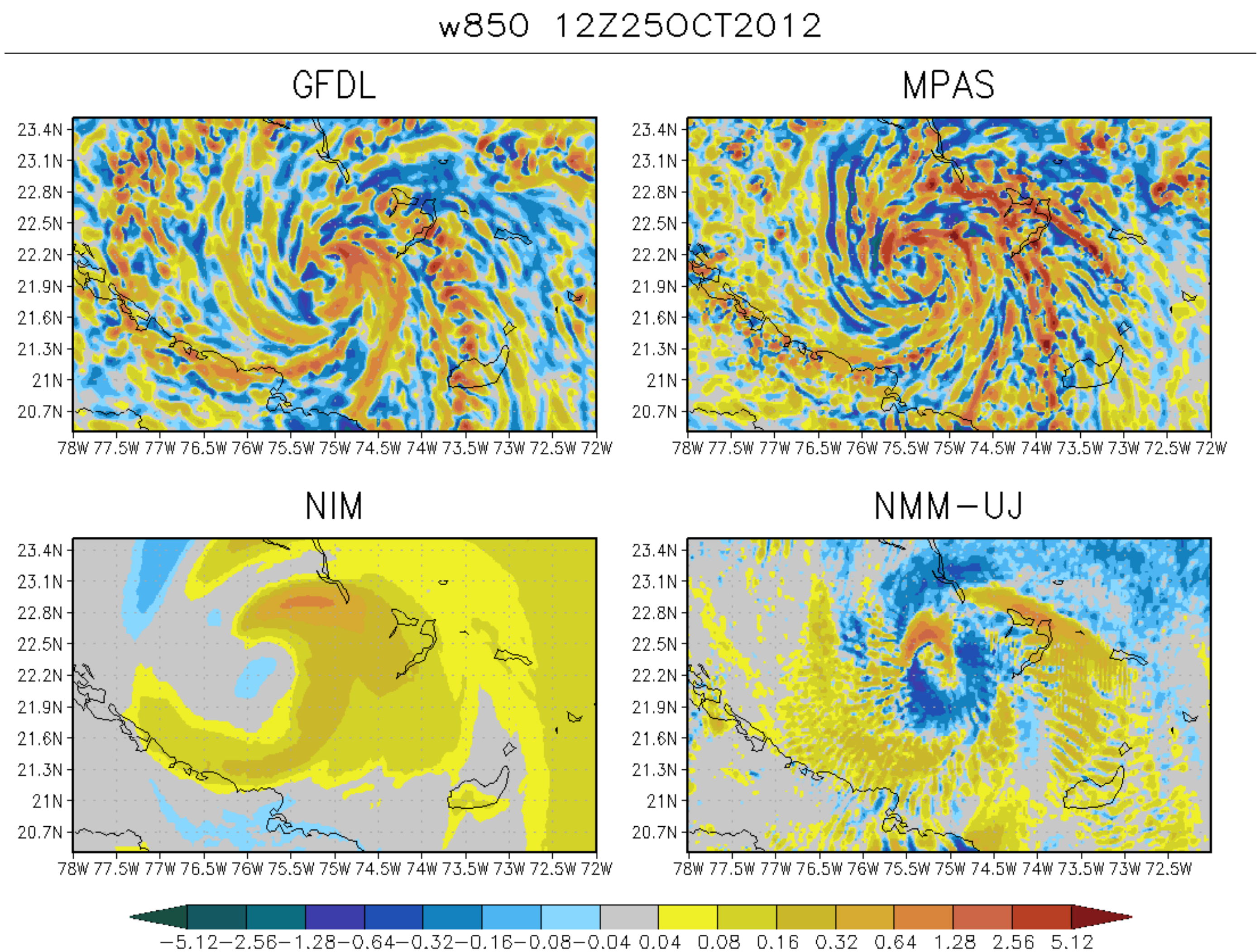
Supercell (2500-m w at 90 mins, 4-km resolution)



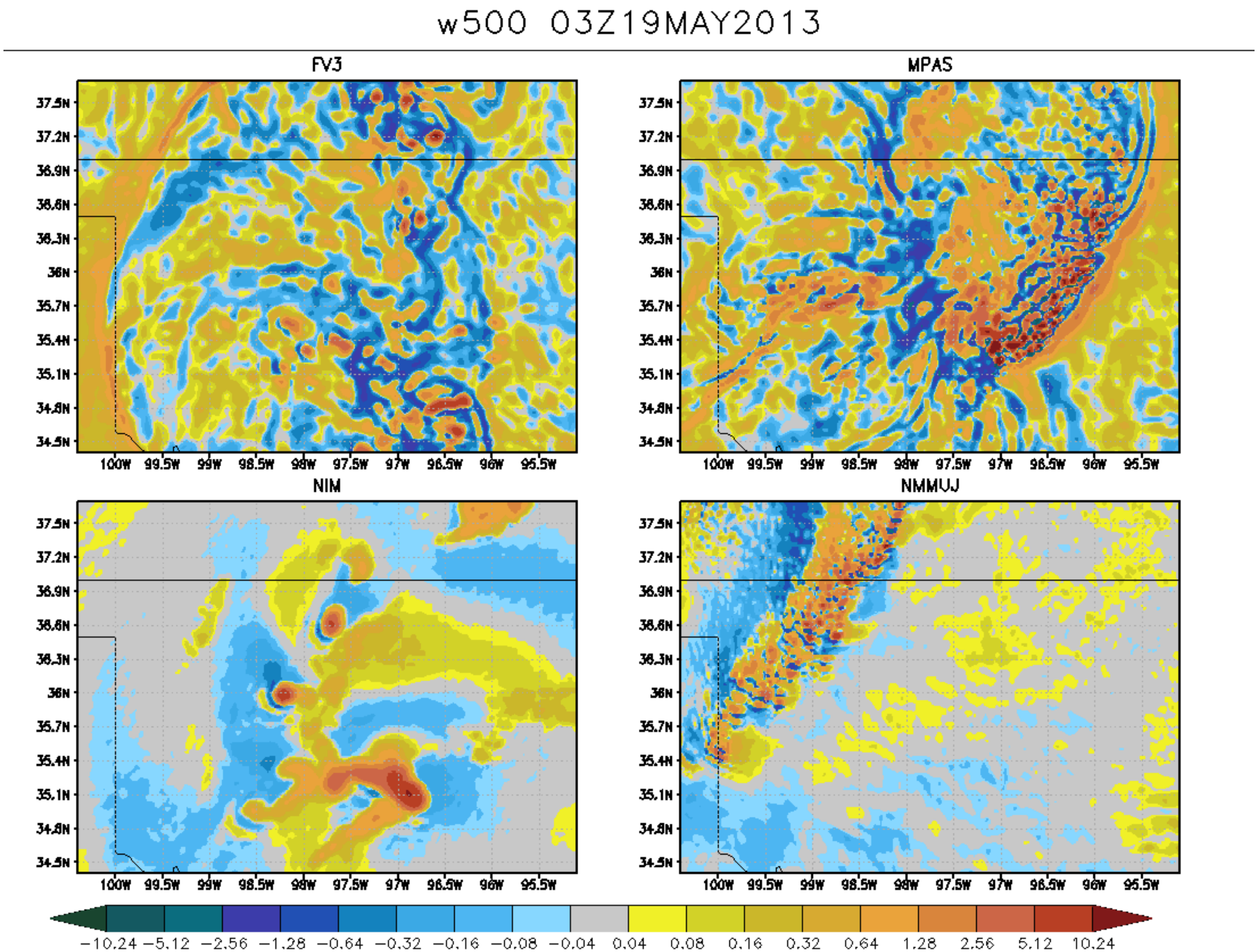
72-h 3-km Forecast Test

- 'Stress-test' dycores by running with full-physics, high-resolution orography, initial conditions from operational NWP system
  - Different physics suites used in each model
- Two cases chosen:
  - Hurricane Sandy 2012102418 (also includes WPAC typhoon)
  - Great Plains tornado outbreak (3-day period beginning 2013051800). Includes Moore OK EF5 tornado around 00UTC May 19
- Focus not on forecast skill, but on ability of dycores to run stably and produce reasonable detail in tropical cyclones and severe convection
  - Also look at global quantities like KE spectra, total integrated precipitation/water vapor/dry mass

Hurricane Sandy (w at 850 hPa)



Moore Tornado (w at 500 hPa)



Idealized Testing Summary

- ***FV3, MPAS*** produced highest quality solutions overall
  - More similar to each other than other models for all tests
- ***NIM*** produced reasonable mountain wave and supercell solutions
  - Excessive noise near grid scale in baroclinic wave solution
  - Full physics forecasts excessively damped
- ***NEPTUNE*** was not able to produce full physics 3-km forecasts
  - Baroclinic wave too smooth, 4-km supercell not split by 90 mins
- ***NMM-UJ*** did not produce realistic solutions for the mountain wave and supercell tests
  - Vertical velocity fields from full physics forecasts did not show signatures expected from resolved convection

NGGPS Phase 1 Testing Project Summary Assessment

	Idealized Tests	3-km, 3-day forecasts	Performance	Scalability	Nesting or Mesh Refinement	Software Maturity
FV3	🟢	🟢	🟢	🟢	🟢	🟢
MPAS	🟢	🟢	🟡	🟢	🟢	🟢
NIM	🟡	🔴	🟢	🟢	🔴	🟢
NMM-UJ	🔴	🟡	🟢	🟢	🟡	🔴
NEPTUNE	🟡	🔴	🔴	🟢	🟢	🔴

🟢 Meets or exceeds readiness for needed capability
🟡 Some capability but effort required for readiness
🔴 Capability in planning only or otherwise insufficiently ready

Requirement Categories

- Model development
- Framework
- Physics and chemistry
- Data assimilation
- Ensemble modeling
- Weather prediction
- Seasonal prediction
- Hurricane prediction
- Space weather prediction
- Air quality prediction
- Adaptability and flexibility

Model development

- EMC global branch must ***own*** the operational code
  - Master version on local repository
  - Agile development for NCEP needs
- O2R2O2R2O…
  - Regular O2R and R2O synchronization
  - Probably need oversight board

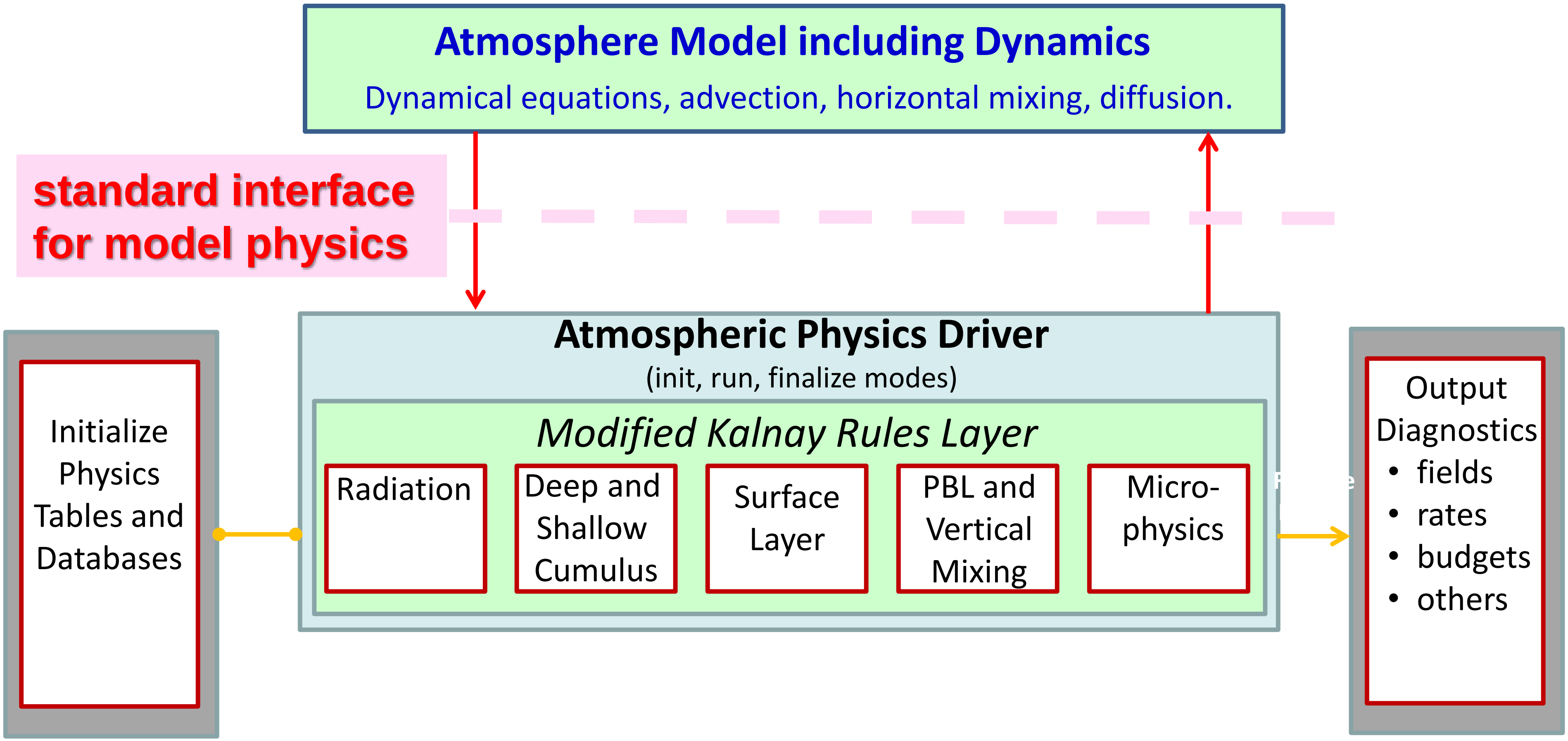
Framework

- Model must be run within NEMS (NOAA Environmental Modeling System)
  - ESMF gridded component wrapper
    - Init, Run, Finalize
    - Import State, Export State all in arguments
    - Standard metadata
  - Output through export state to be written by separate NEMS Write component

Physics and chemistry

- Single column physics and chemistry
- Currently time-split from dynamics in the GFS, and each parameterization can have its own time scheme, including implicit schemes
- Want efficient dynamics (so physics and chemistry can take proportionately more time)
- Want fast accurate conservative monotonic transport
- Potential for varying horizontal resolution with height (higher in PBL, lower in stratosphere)
- Potential for different grids for some physics
- **Use generic NUOPC GFS physics driver**

NUOPC Physics Driver Schematic



Data assimilation

- Non-orthogonal variable resolution grid
  - Definition of background error will be difficult
    - Different error characteristics at different locations
    - Lower resolution ensembles may not be representative
    - Appropriate stochastic part of ensemble changes over grid
  - Should calculate O-B on original grid, a capability that isn't ready
  - If increments are on regular grid, there could be resolution issues
  - Should be done in model's vertical coordinate
- Non-hydrostatic
  - Insufficient observing system to define non-hydrostatic component (radar?)
  - Additional degrees of freedom in analysis – balance more difficult
  - Analysis increment assumed hydrostatic?
- 4D-var requires adjoint and tangent linear of forecast model
- Impact on computational expense of assimilation system?

Ensemble modeling

- Stochastic forcing
  - Requires operations on the dynamics grid
  - Dynamics may need to provide grid services
- Restart capability
- Fault tolerance

Weather prediction

- Current requirement is **1** 24-hour high resolution forecast every **500** seconds of wall time on **38%** of operational computer
- All are important, but *speed* and *resolution* relatively more important than *conservation* within dynamic core for short forecasts
- Errors in dynamics do not need to be less than errors in physics or initial conditions
- General tracer capability for gases, aerosols, second order fields (like TKE), etc.

Seasonal prediction

- Physics (and coupling) tends to be more important than dynamics seasonally
- All are important, but *speed* and *conservation* relatively more important than *resolution* within dynamic core for short forecasts
- Errors in dynamics do not need to be less than errors in physics or boundary forcing
- Restart capability
  - Must be able to get bit-identical answer if configured properly

Hurricane prediction

- NEMS hurricane nests dycore requirements
  - Two-way feedback (upscale feedback captures effect of hurricane on environment)
  - Storm-following nests
- NEMS hurricane nests other requirements
  - Scalable physics
  - Multi-grid combined GRIB products directly from model (plus custom hurricane products)
  - Coupled atmos-wave-ocean

Space weather prediction

- Need 600 km top, so at 10% of Earth's radius, errors occur unless deep atmosphere assumption (r=a+z) is used.
- Must tolerate temperatures of over 2000 K and winds over 1000 m/s
- Also requires O and O_2 be treated as separate tracers carrying their respective specific heat and gas constant.

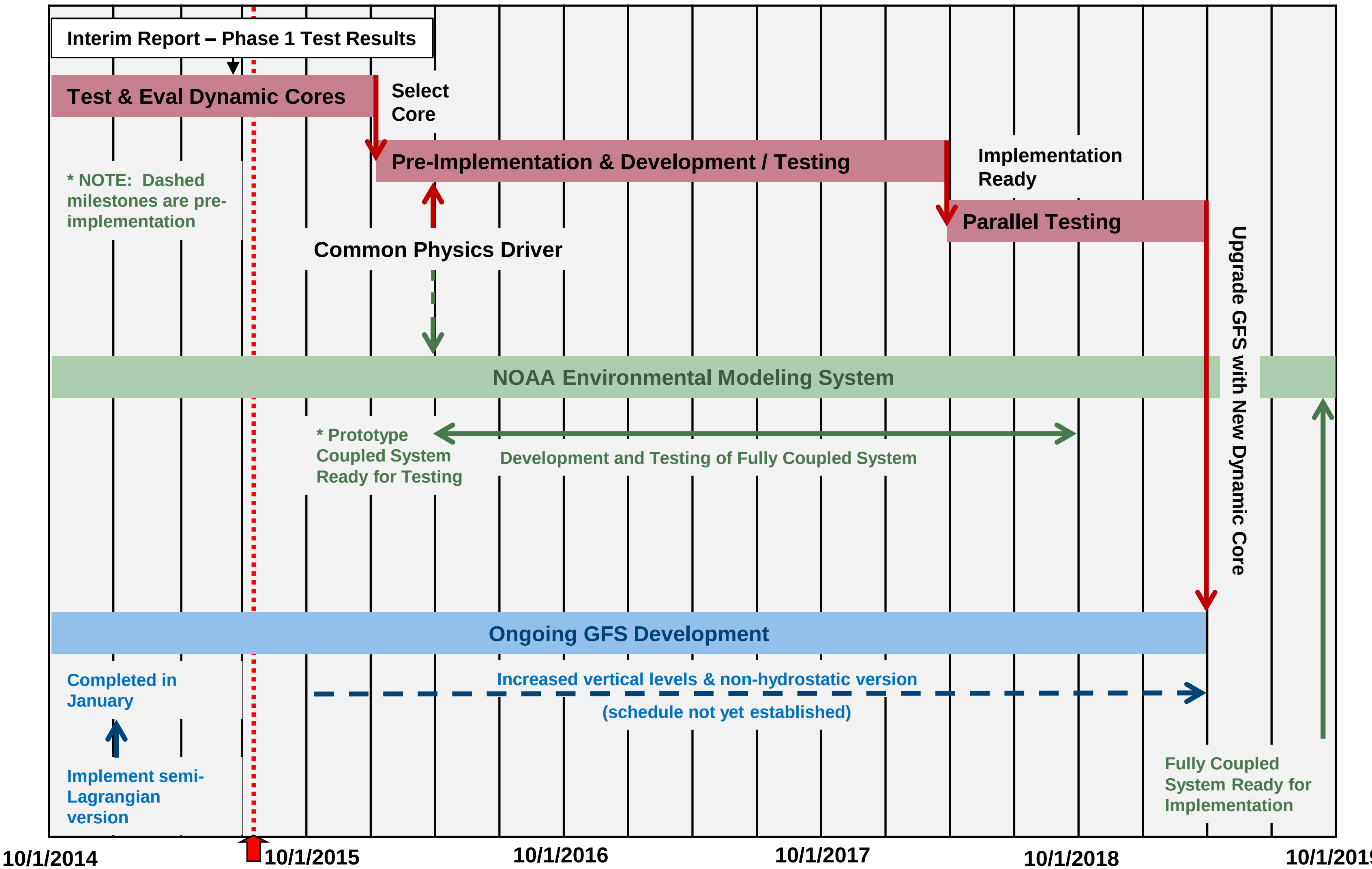
Air quality prediction

- Requires fast accurate conservative monotonic transport of tracers specified at run time.
- Some tracers (gases) may carry their own gas constant, some (aerosols) may not, and some (TKE) may not contribute mass

Adaptability and flexibility

- It is a massive ordeal to replace a dynamical core in operations.
- Therefore any replacement must last for a long time.
- Therefore the overarching requirement of a dynamical core is that it be adaptable and flexible to future upgrades, even those we cannot anticipate now.

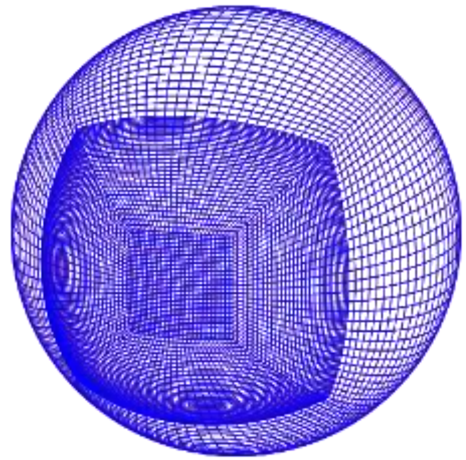
NGGPS Implementation

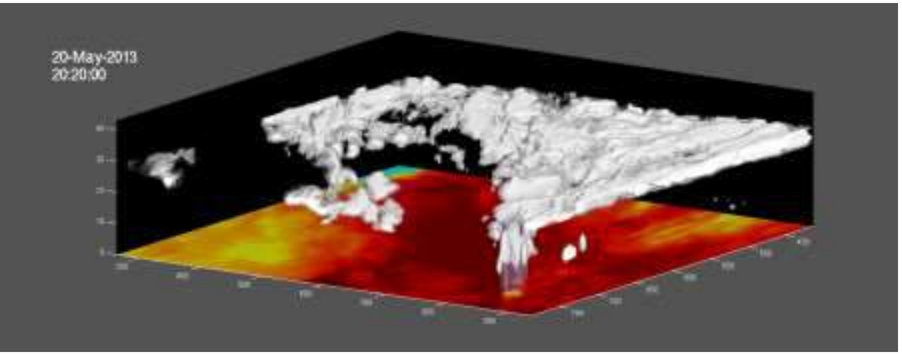


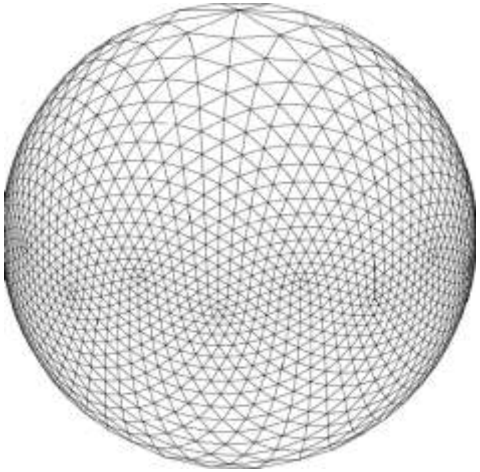
Next Generation Global Prediction System (NGGPS)

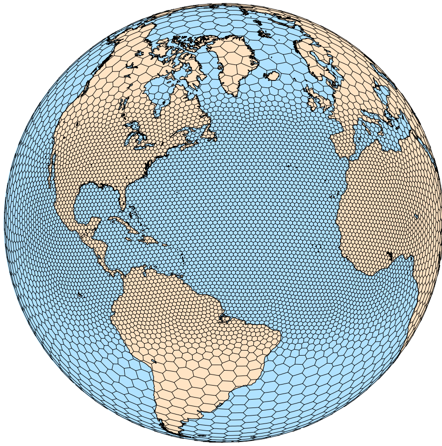
Nesting and Convective Systems

Team Plans and Activities





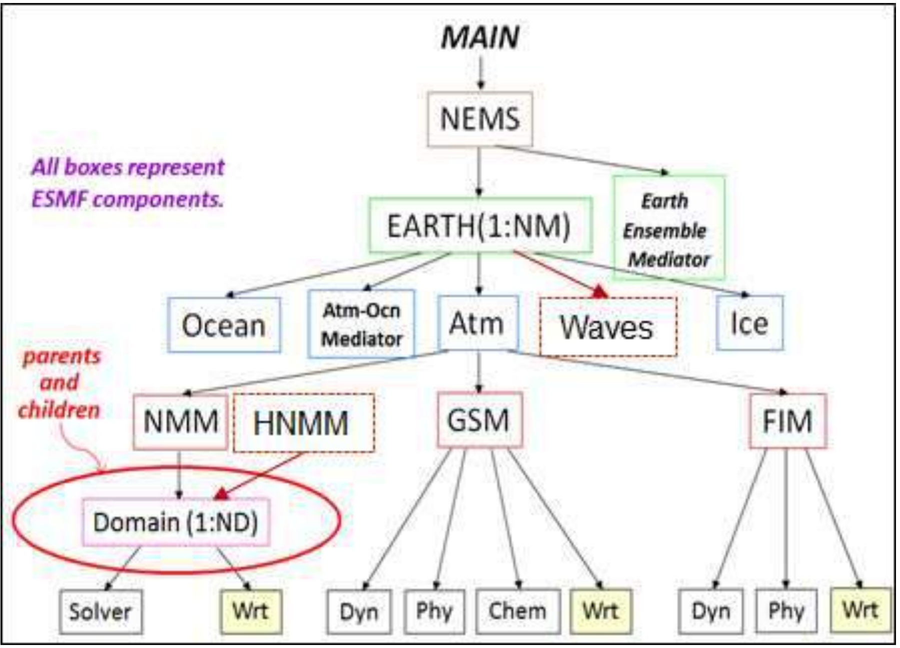


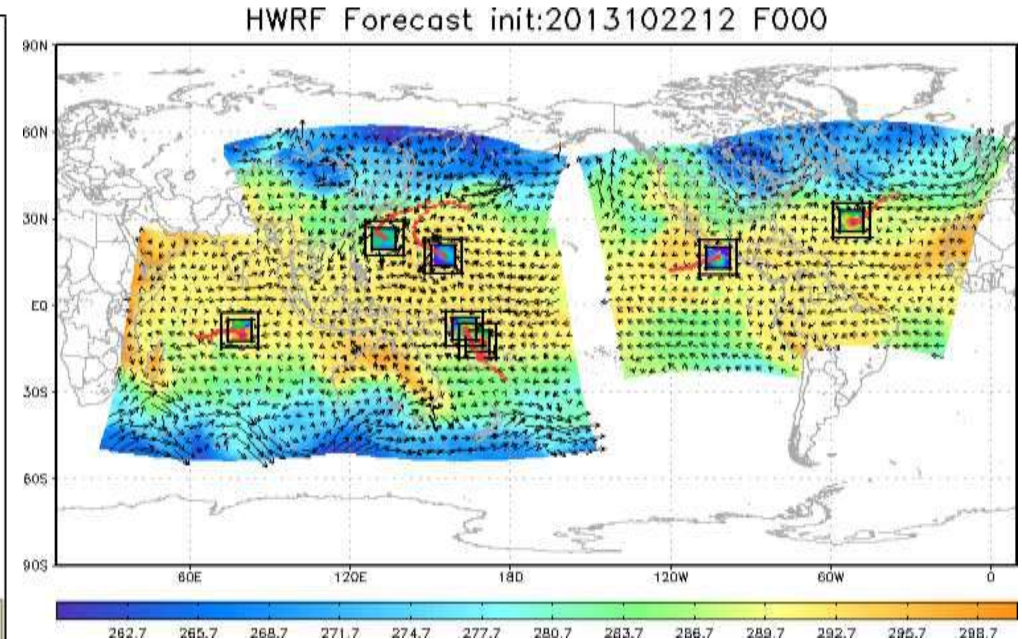


General Requirements for Operational Nesting or Grid Enhancement

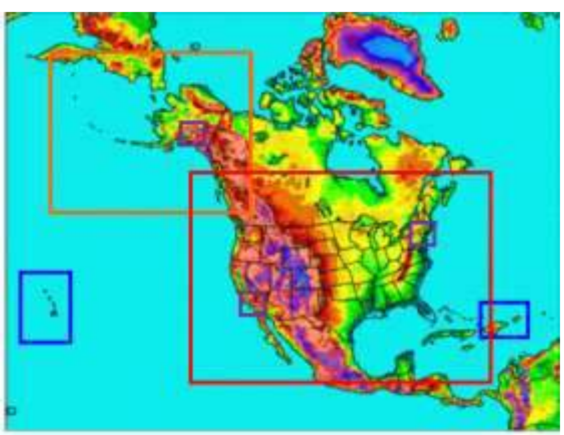
- Static/moving
- 1-way/2-way interactive (nests)
- Multiple nests run simultaneously
- Bit reproducible and restartable (static/moving/ 1-way/2-way)
- *Very fast and efficient!*
- Dynamics, physics and initialization appropriate and applicable for high-resolution nests within the global model

Current Operational Nests for Regional Models: NAM and HWRF





2015 HWRF Global Tropical Cyclone Forecasts: 7-storm capability



NAM: Parent runs at 12 km to 84 hr
Four static nests run to 60 hr

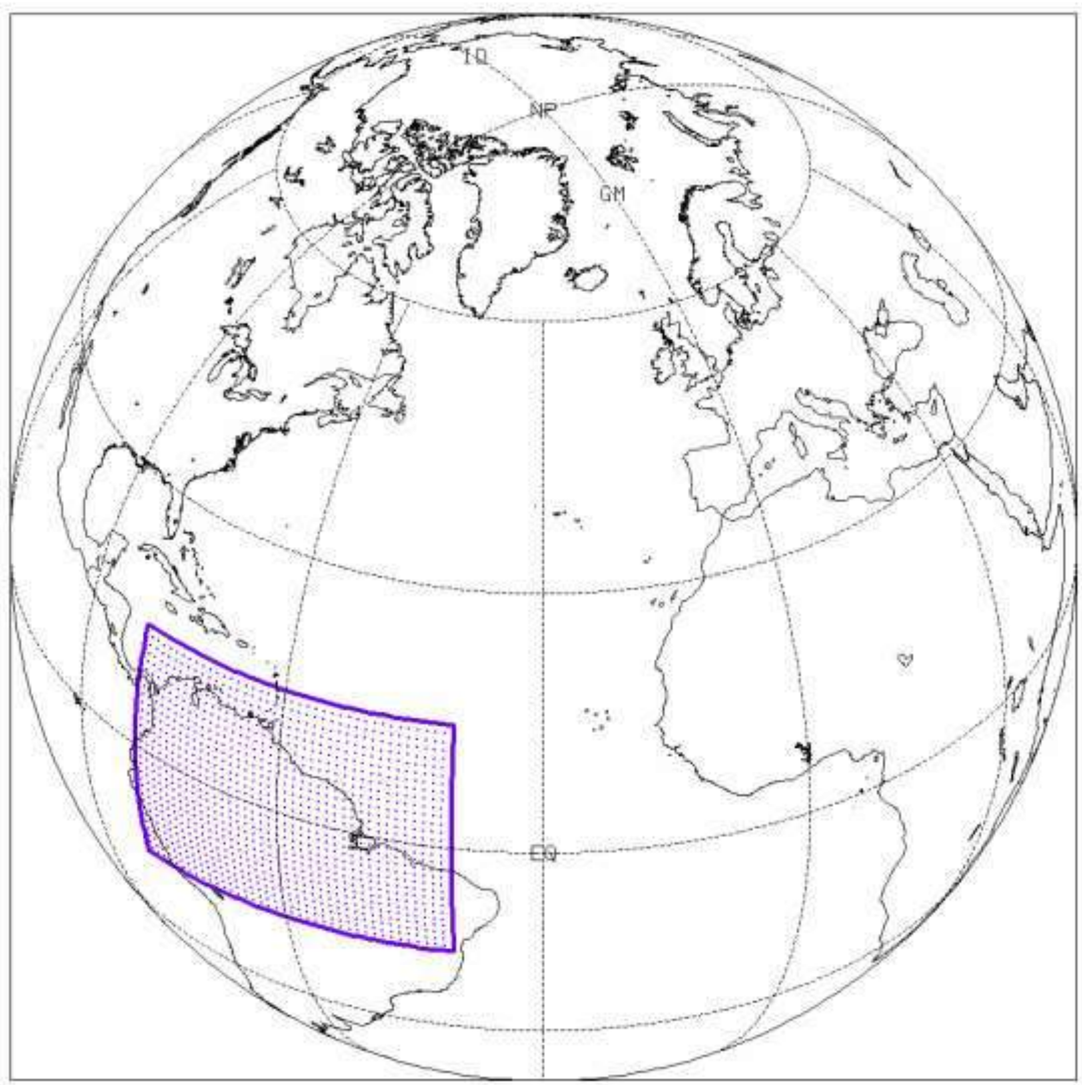
4 km CONUS nest (3-to-1)
6 km Alaska nest (2-to-1)
3 km HI & PR nests (4-to-1)

Single relocatable 1.33km or 1.5km FireWeather grandchild run to 36hr (3-to-1 or 4-to-1)

HWRF: Parent runs at 18 km with storm following 2-way interactive nests at 6 km and 2 km resolution out to 126 hr

- **Coupled to Ocean (and Waves)**
- **ENSVAR inner core aircraft DA**
- **Seven storms all over the world**
- **Transition to NMMB/NEMS in progress**

Parent-associated nest vs. freestanding nest on a global lat/lon

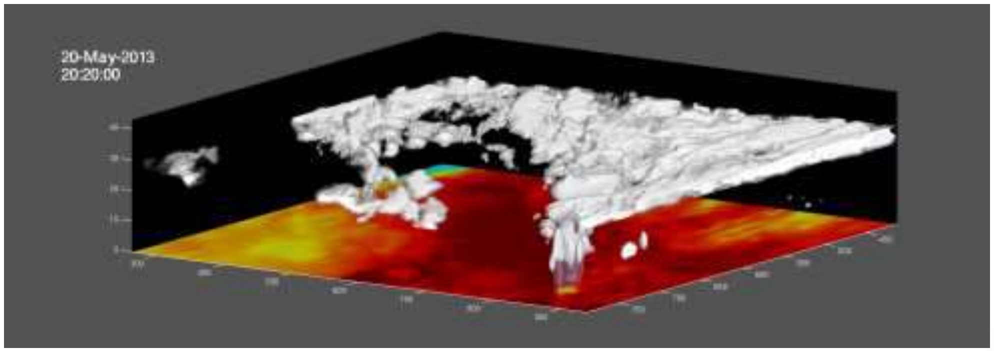


Freestanding => on a projection different from the parent's

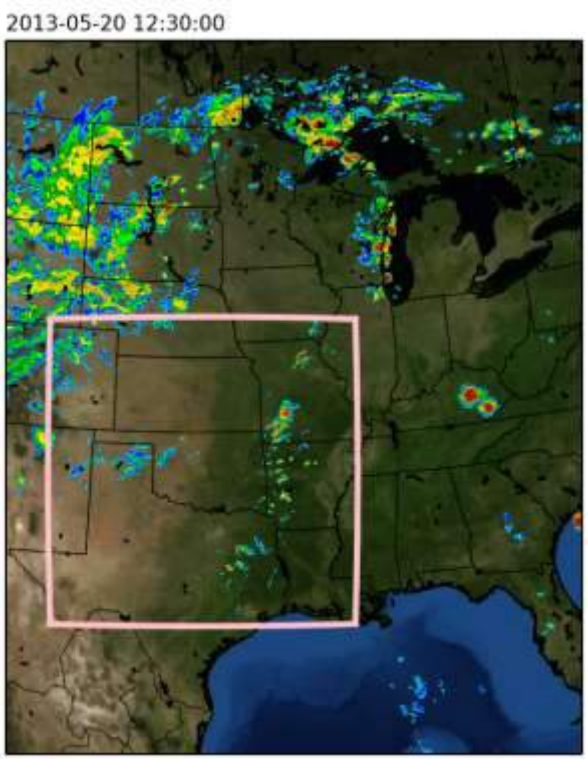
Actively being developed for NMM in NEMS framework. Courtesy: Tom Black

Two-Way Nesting Capabilities in GFDL FV3

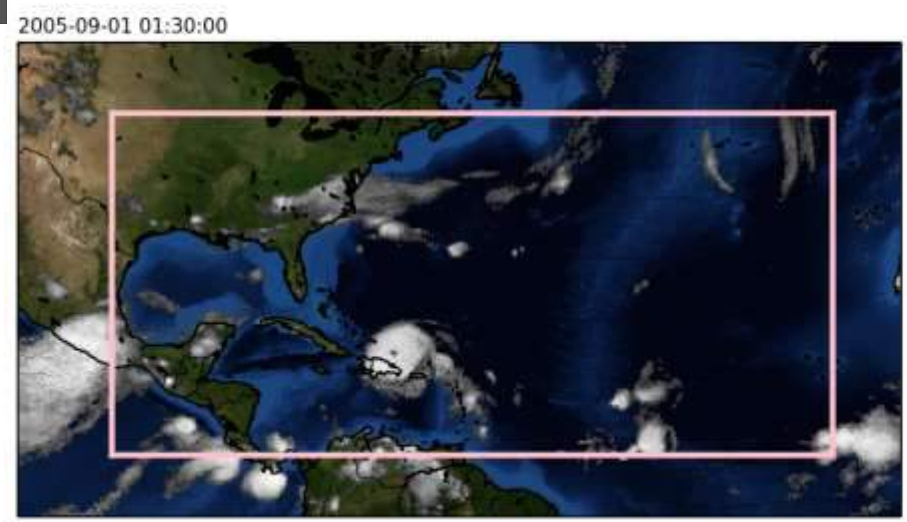
(Recent developments using HiRAM and FV3)



Examples of high-resolution nested grid simulations using HiRAM and FV3



three-day HiRAM forecasts of severe convection during the Moore, OK tornado outbreak of May 2013, in a simulation nesting down to 1.3 km over the southern plains (using HIWPP 3km global runs)



Year-long nonhydrostatic HiRAM simulation using 2005 SSTs, using an 8-km nest over the tropical Atlantic

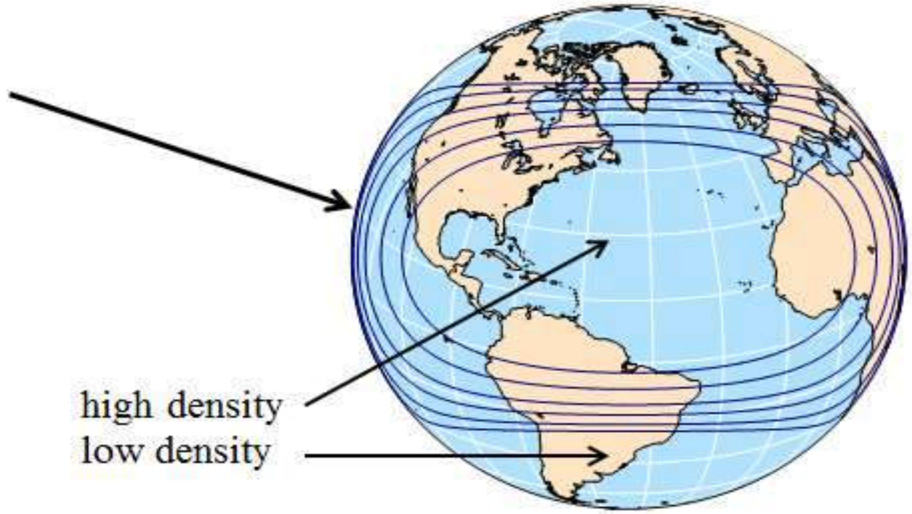
Slide courtesy: Lucas Harris, GFDL

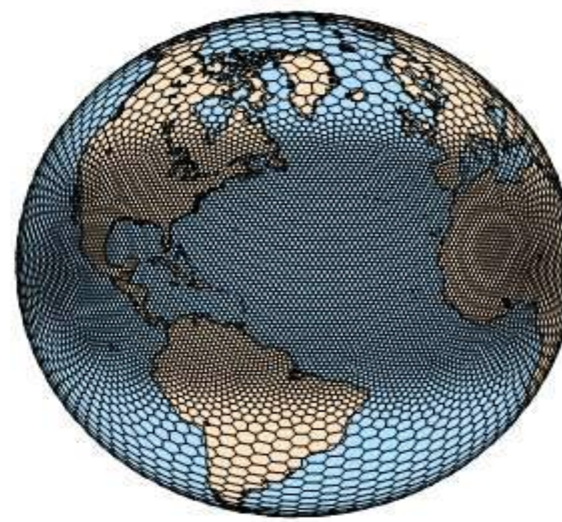
Mesh Refinement Capabilities in NCAR MPAS: Mesh Generation

(1) User-specified density function

(2) Lloyd's method

1. Begin with any set of initial points (the generating point set)
2. Construct a Voronoi diagram for the set
3. Locate the mass centroid of each Voronoi cell
4. Move each generating point to the mass centroid of its Voronoi cell
5. Repeat 2-4 to convergence





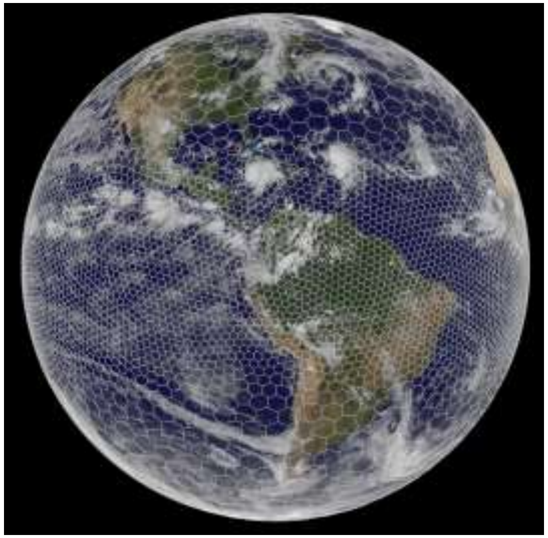
MPAS
Model for Prediction Across Scales

Slide courtesy: Bill Skamarock, NCAR

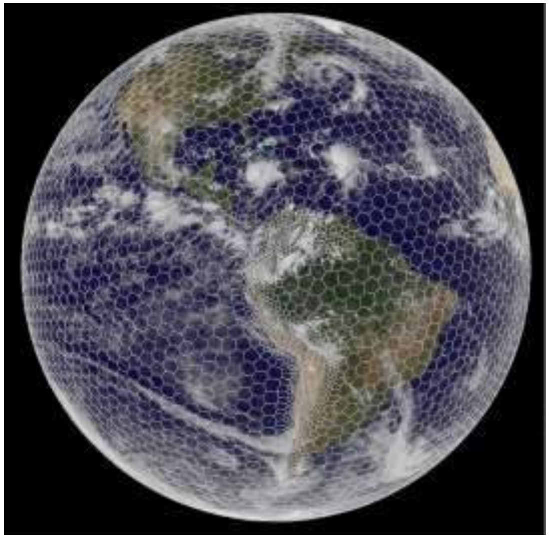
MPAS: Mesh Generation: Lloyd's Method

(iterative, using a user supplied density function)

North American refinement



Equatorial refinement



Andes refinement

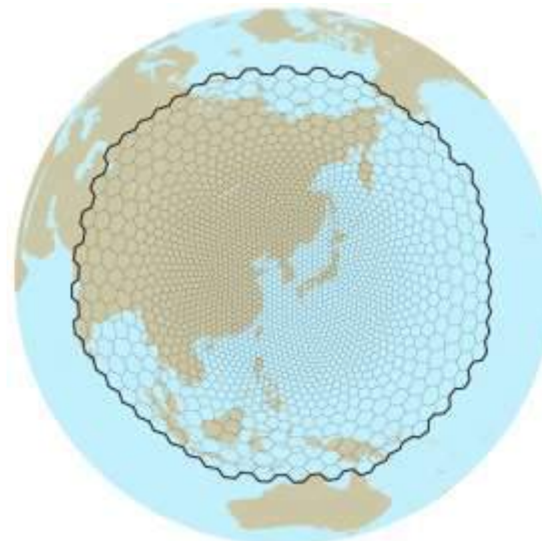
MPAS
Model for Prediction Across Scales

Slide courtesy: Bill Skamarock, NCAR

MPAS: Global Mesh and Integration Options

Global Uniform Mesh

Global Variable Resolution Mesh



Regional Mesh - driven by
(1) previous global MPAS run
(no spatial interpolation needed!)
(2) other global model run
(3) analyses

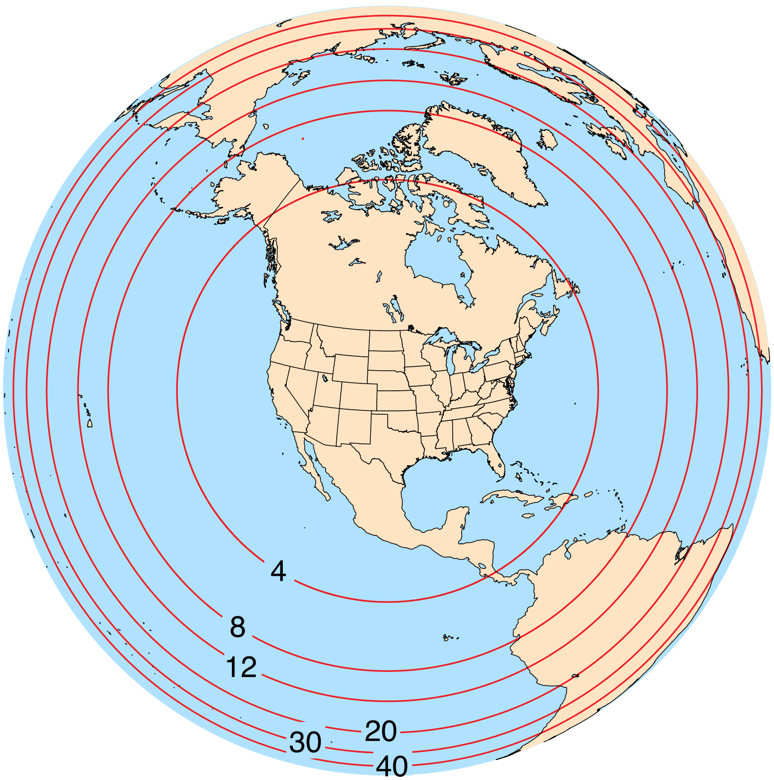
Voronoi meshes allows us to cleanly incorporate both downscaling and upscaling effects (avoiding the problems in traditional grid nesting) & to assess the accuracy of the traditional downscaling approaches used in regional climate and NWP applications.

MPAS
Model for Prediction Across Scales

Slide courtesy: Bill Skamarock, NCAR

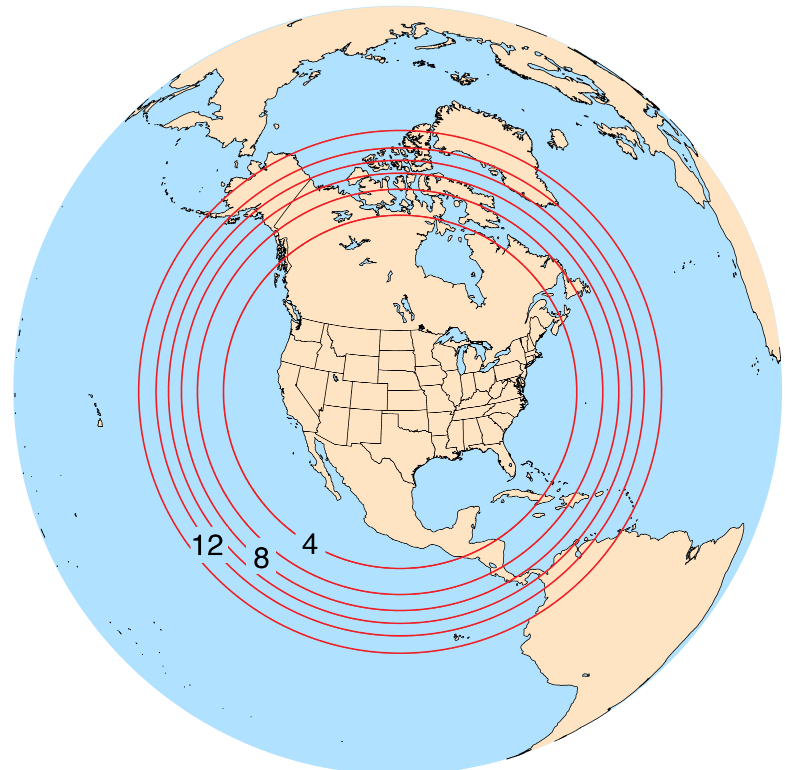
MPAS Forecast Experiments with Variable-Resolution Meshes

HWT Spring Experiment
5-day forecasts, 50 – 3 km mesh 1-31 May 2015



3-50 km mesh, Δx contours 4, 8, 12, 20, 30, 40
approximately 6.85 million cells
68% have < 4 km spacing

PECAN field campaign
3-day forecasts, 15 – 3 km mesh
7 June – 15 July 2015



3-15 km mesh, Δx contours
approximately 6.5 million cells
50% have < 4 km spacing

MPAS
Model for Prediction Across Scales

Slide courtesy: Bill Skamarock, NCAR

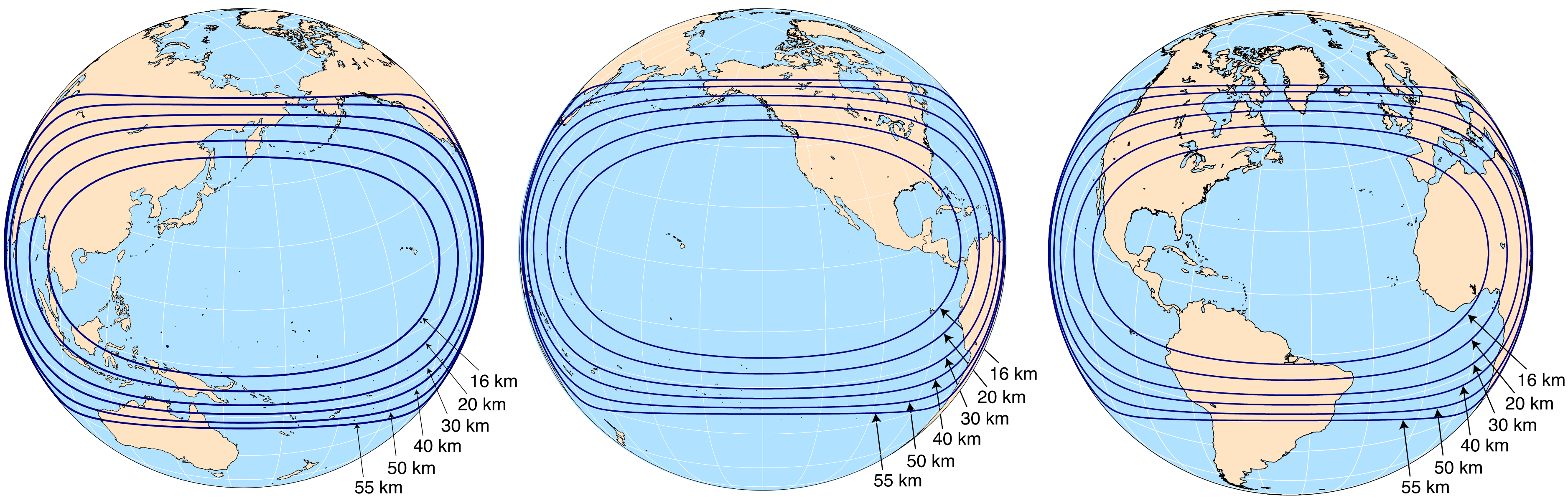
Forecast Experiments with Variable-Resolution Meshes

MPAS-Atmosphere 2013-2014-2015

Tropical Cyclone Forecast Experiments

daily 10-day forecasts during the NH tropical cyclone season

Western Pacific basin mesh | Eastern Pacific basin mesh | Atlantic basin mesh



MPAS
Model for Prediction Across Scales

Slide courtesy: Bill Skamarock, NCAR

Dynamic Core
Phase 2 Testing Plan

- Testing plan drafted by the Test Manager (Jeff Whitaker) - DTG will assess plan
- Planned Phase 2 Testing criteria:
  - Deep atmosphere dynamics
  - Conservation properties
  - Untuned forecast skill and model robustness
  - Model performance with physics
  - Variable resolution/nesting
  - Climate integration performance
  - Adaptable to NEMS/ESMF
- Phase 2 testing will be conducted with a stand-alone GFS based physics package – standardized interface in development at EMC

NGGPS Dynamical Core Priorities?

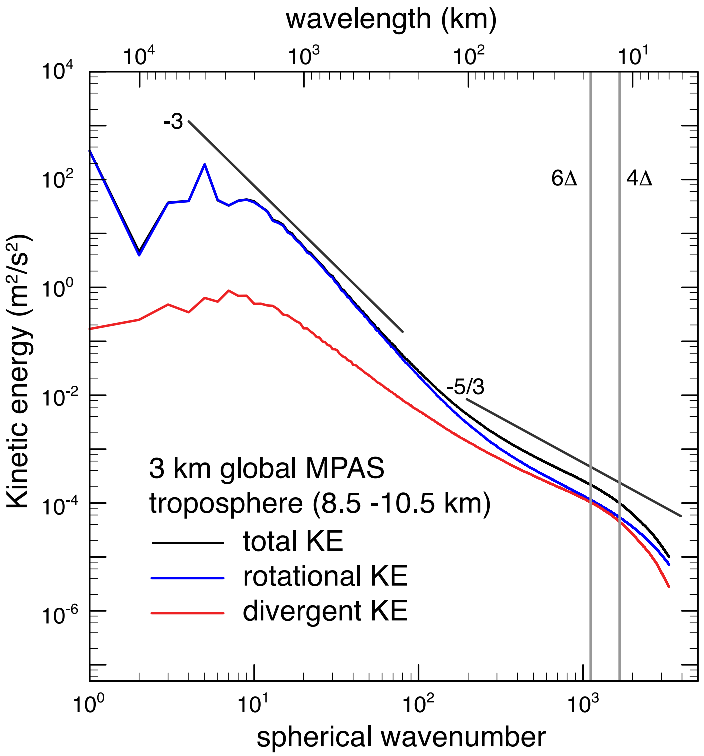
The reason to push global NWP to nonhydrostatic scales is to *begin to resolve* dynamics and physics that were previously unresolvable.

- *Deep Convection*
- *Topography*

15 km global models just beginning to resolve the mesoscale where divergent motions are becoming significant.

3 km models are *convection-permitting*, where divergent motions *are the primary signal*.

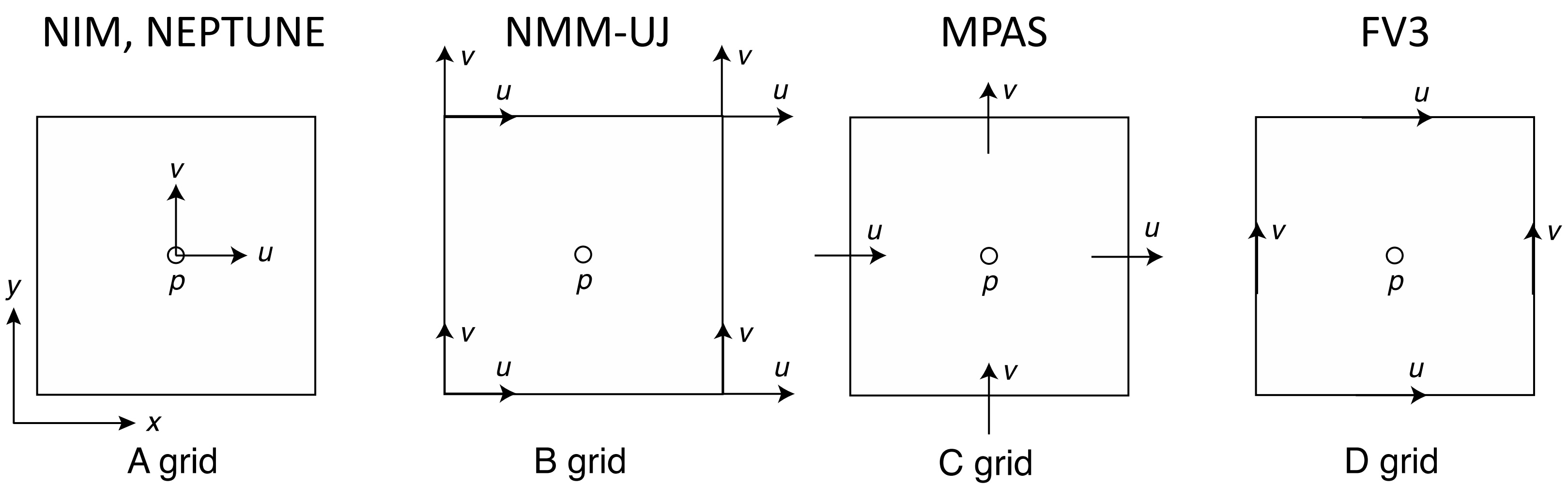
Convection and nonhydrostatic motions are at the margins of model resolution for O(km) grids.



Given envisioned unified global-regional NWP model applications, characterizing the nonhydrostatic-scale capabilities (effective resolution) of the NGGPS dynamical cores is a critical task.

Phase 2 Test Plan Considerations
Dynamical Core Differences

One of the major differences between the two remaining cores is their grid staggering. MPAS uses a C-grid staggering and FV3 uses a D-grid staggering. The different grids have implications for resolving mesoscale and cloud-scale (divergent) motions.

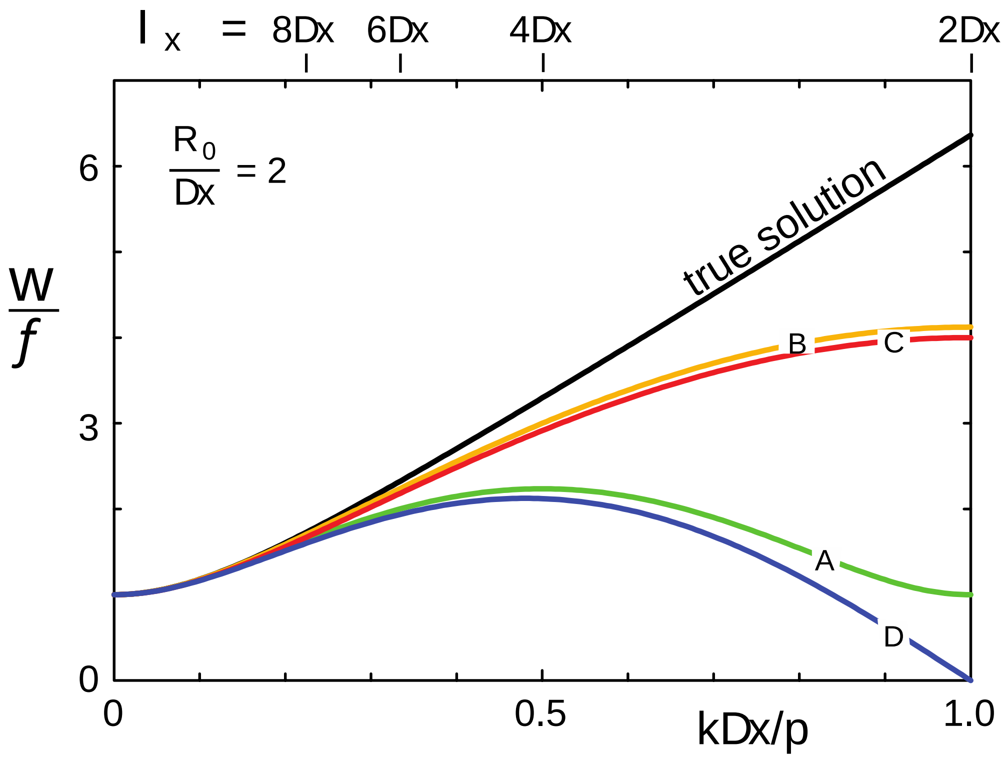


(Illustrated for a rectangular grid)

Phase 2 Test Plan Considerations
Dynamical Core Differences

What does theory tells us about the capabilities of these different grid staggerings?

1D Linearized shallow-water equations (inertia-gravity waves).



Pressure-gradient/divergence averaging for the A and D grids leads to poor response for the shorter wavelength modes.

Mesinger and Arakawa (1976), figure 3.2: *"The figure vividly illustrates the inadequacy of the lattices (D) and (A)."*

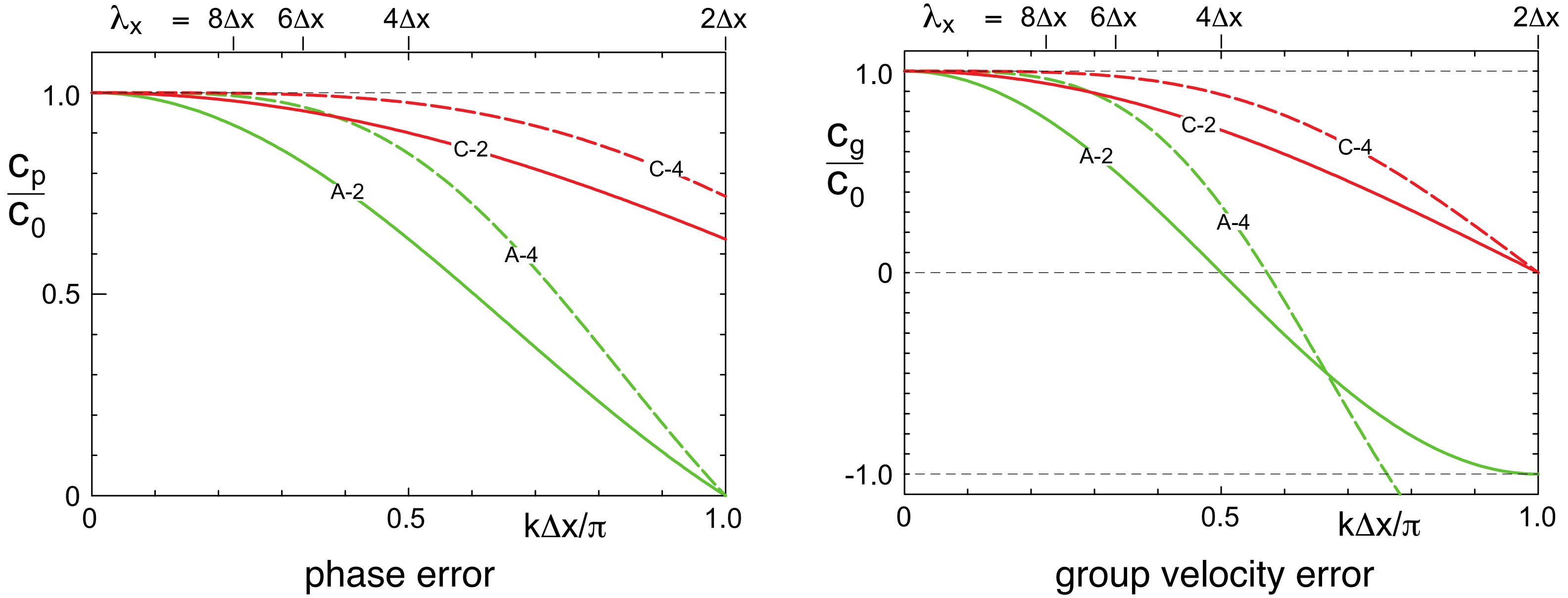
Mesinger and Arakawa (1976), Arakawa and Lamb (1977)

Phase 2 Test Plan Considerations
Dynamical Core Differences

What does theory tells us about the capabilities of these different grid staggerings?

1D Linearized shallow-water equations, *f = 0* (gravity waves).

(Note: 1D f=0, A and D grids are identical, B and C grids are identical)

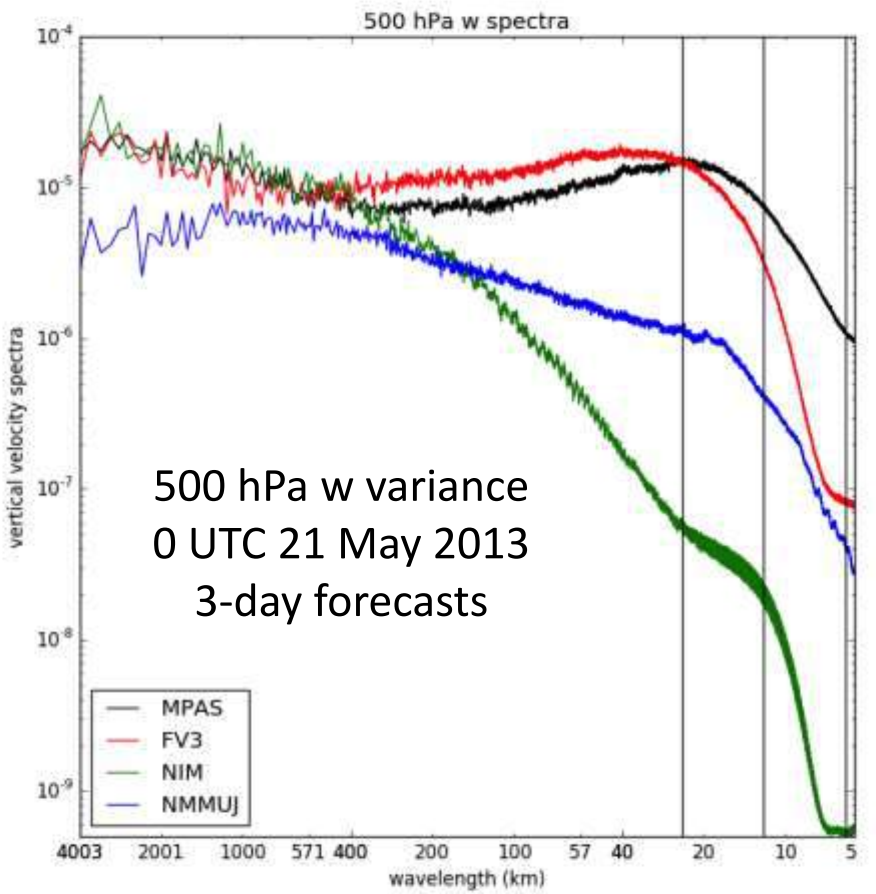


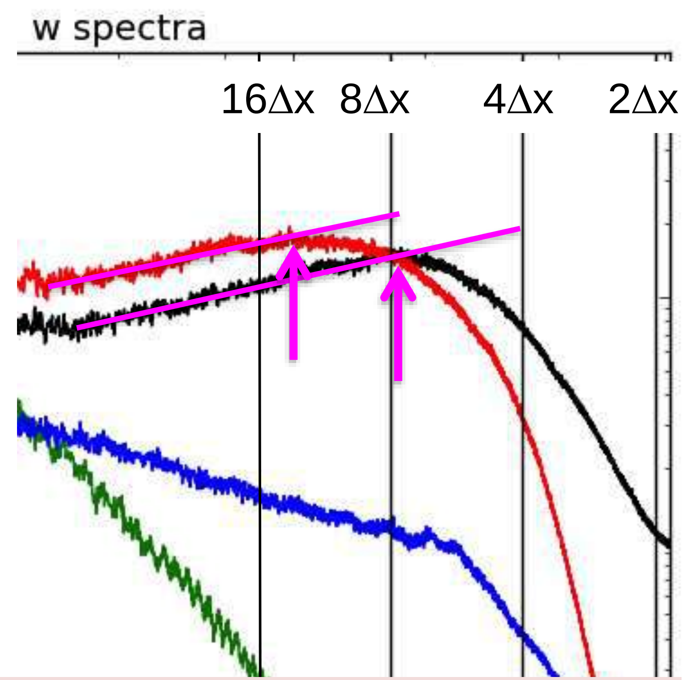
Given their larger errors, A and D grids need more filtering than B and C grids.

Phase 2 Test Plan Considerations
Dynamical Core Differences – Test Results

Do the Phase 1 test results support the theory and the expectation of increased filtering for the A and D grids?

3 km forecasts NGGPS Phase 1 forecast results (Whitaker and Pegion, May 2015)



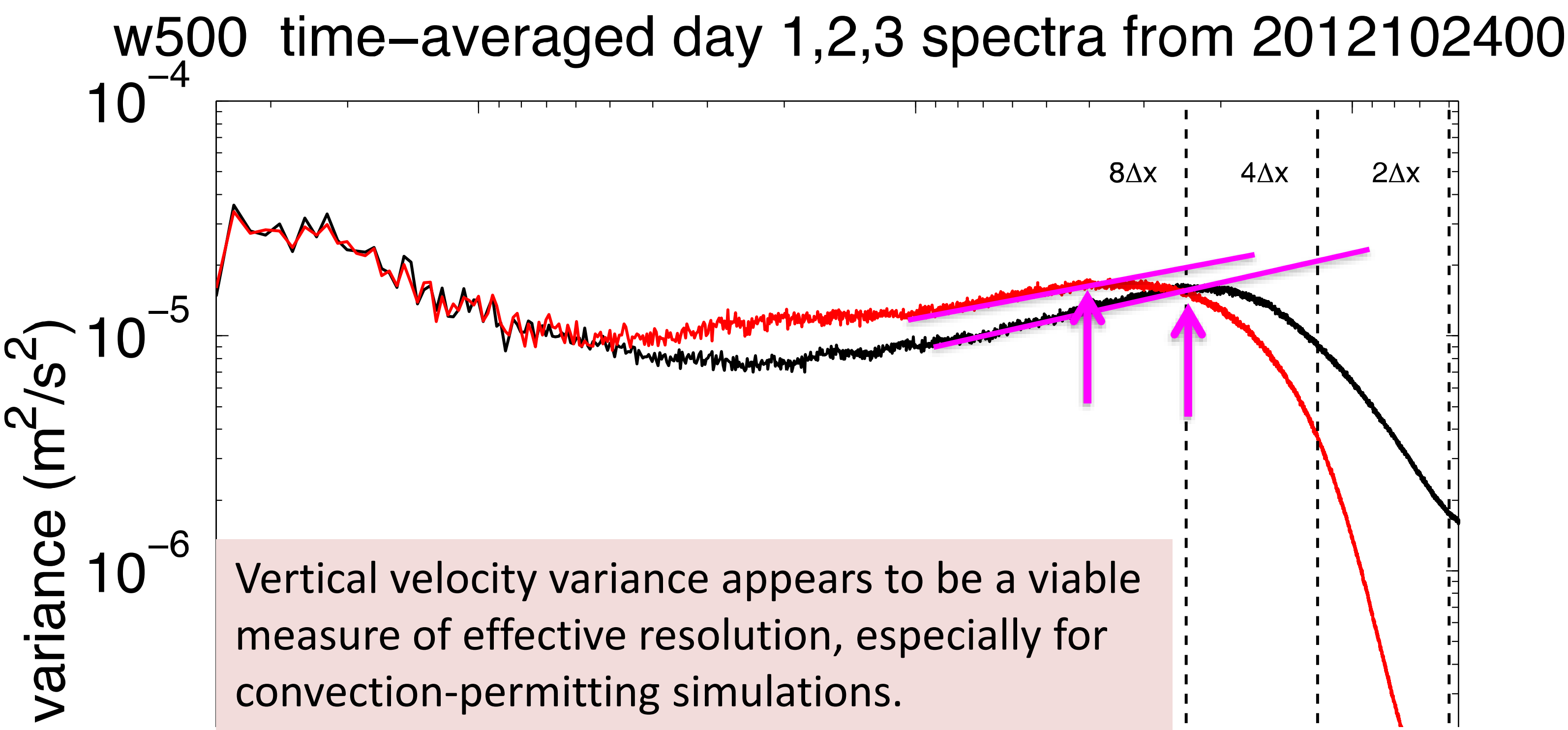


FV3 is more damped than MPAS and its effective resolution is 1.5-2x less.

Phase 2 Test Plan Considerations
Dynamical Core Differences – Test Results

Do the Phase 1 test results support the theory and the expectation of increased filtering for the A and D grids?

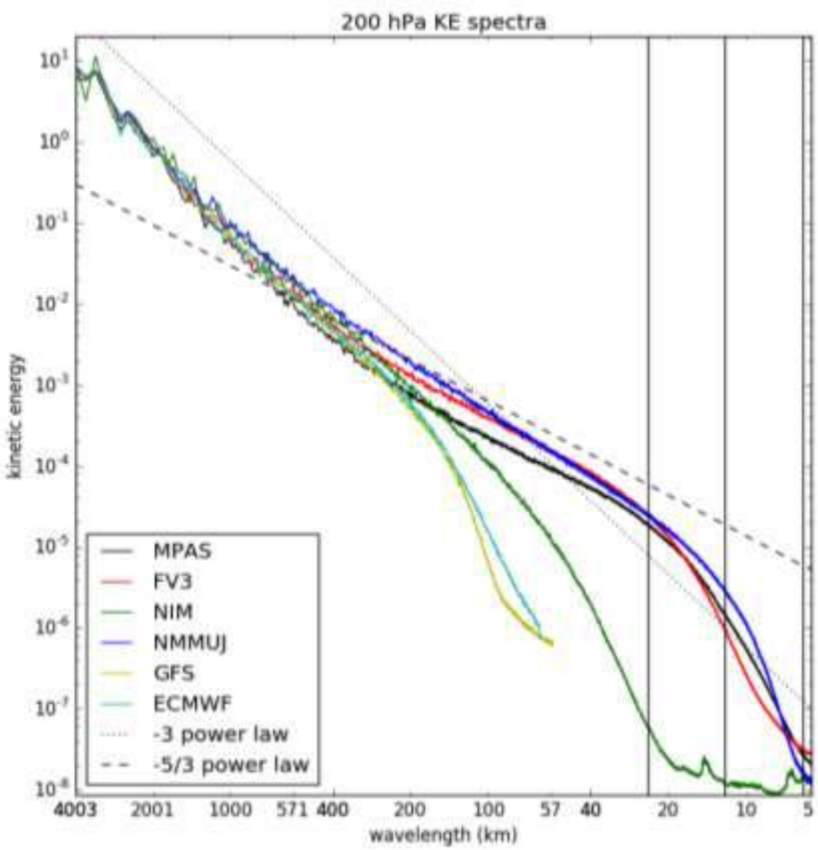
3 km forecasts NGGPS Phase 1 forecast results, further analysis (Sandy Case)



Vertical velocity variance appears to be a viable measure of effective resolution, especially for convection-permitting simulations.

Phase 2 Test Plan Considerations
Dynamical Core Differences – Test Results

Do the Phase 1 test results support the theory and the expectation of increased filtering for the A and D grids?



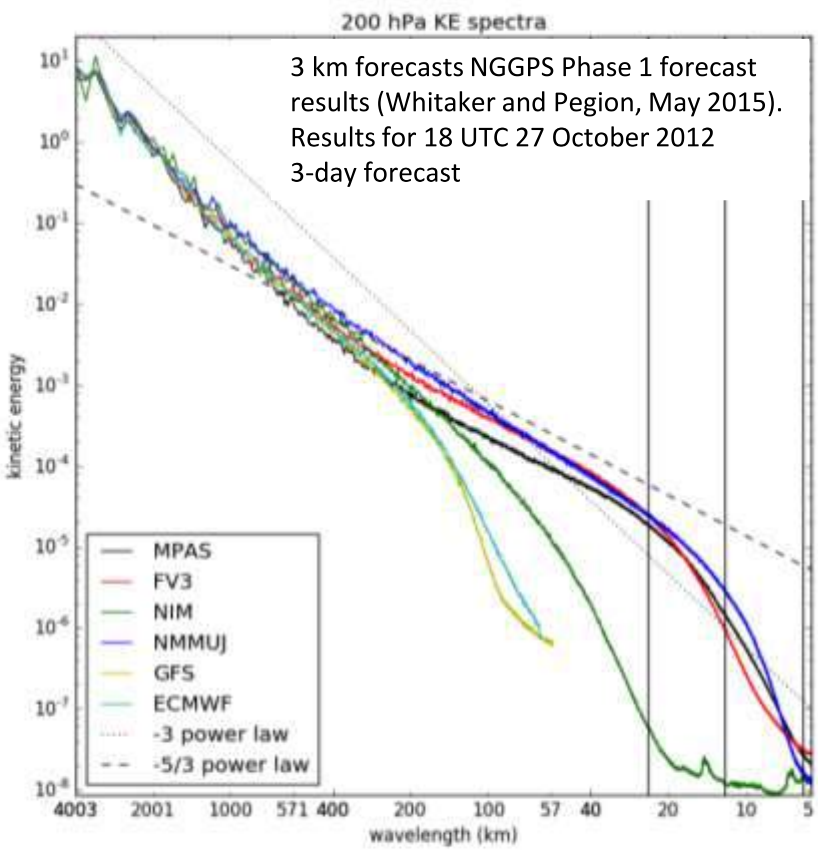
3 km NGGPS Phase 1 forecast results (Whitaker and Pegion, May 2015).
Results for 18 UTC 27 October 2012
3-day forecasts

The global KE is more difficult to interpret with respect to effective resolution.

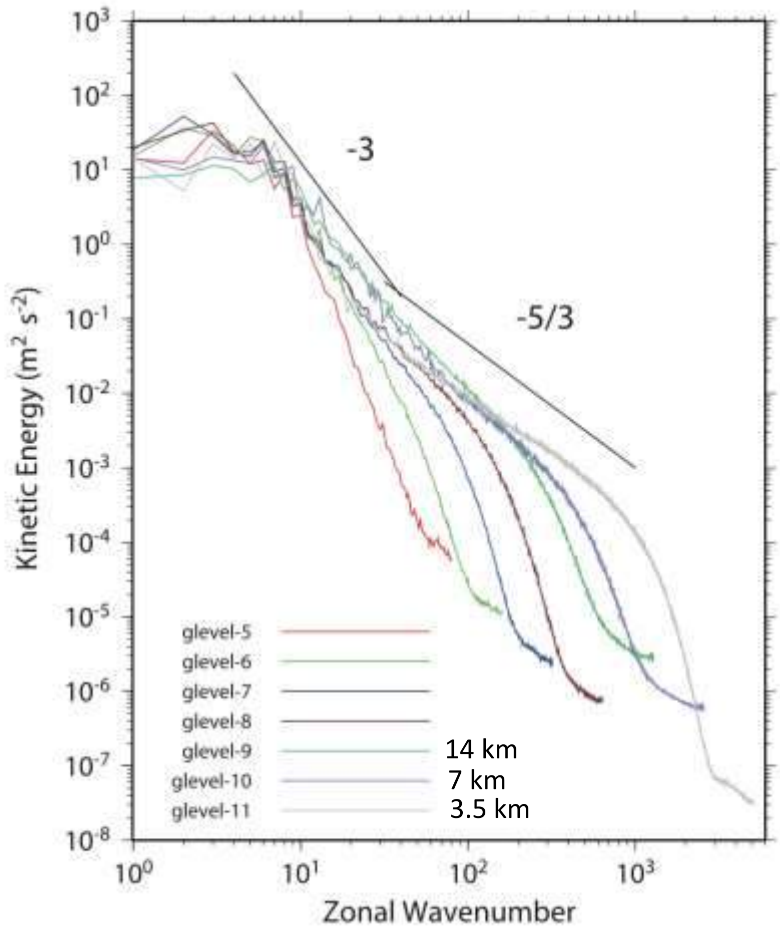
Are the differing kinetic energy levels in the mesoscale significant?

Phase 2 Test Plan Considerations
Dynamical Core Differences – Test Results

Are the differing kinetic energy levels in the mesoscale significant?



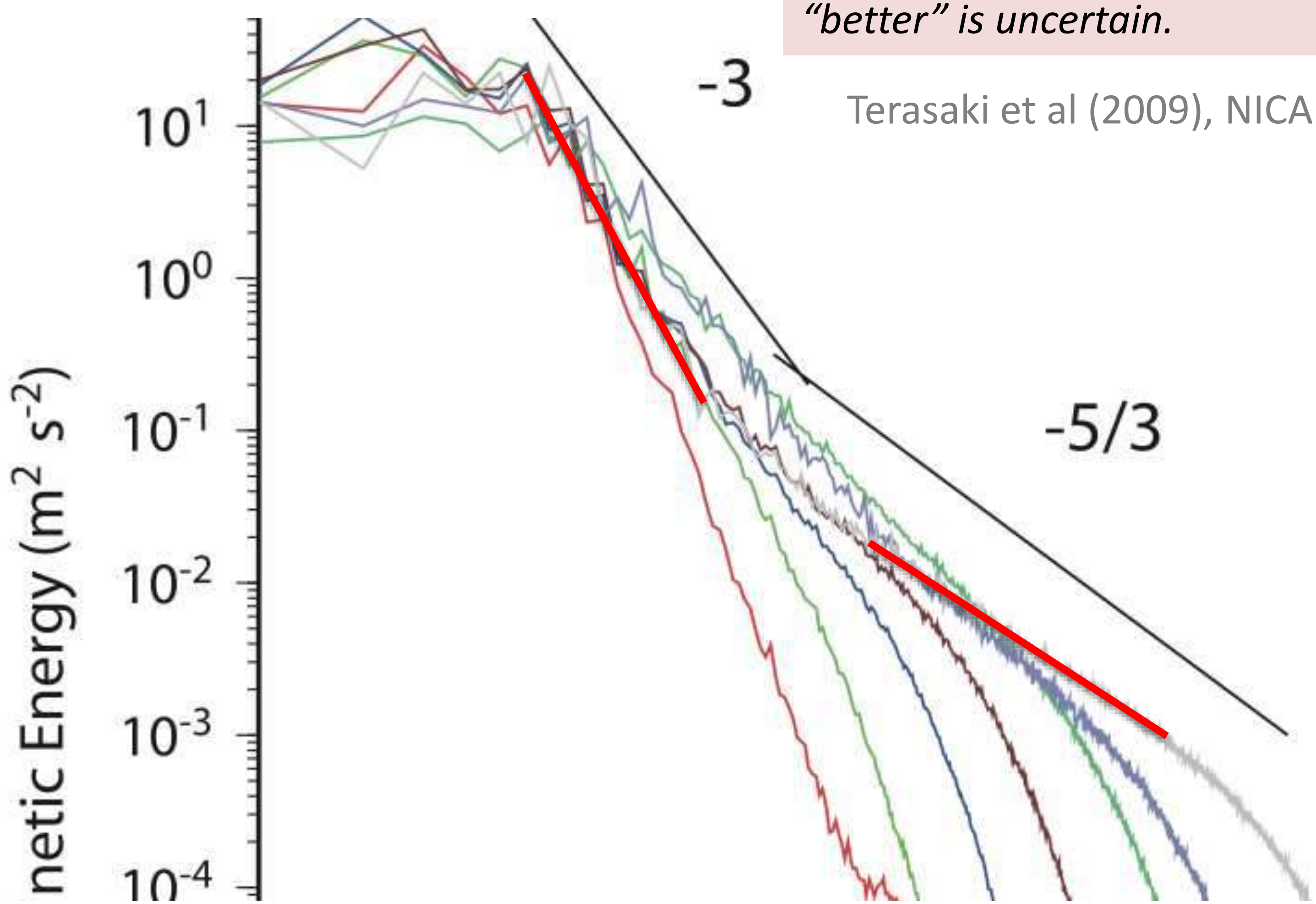
Terasaki et al (2009), NICAM



Phase 2 Test Plan Considerations
Dynamical Core Differences – Test Results

Are the differing kinetic energy levels in the mesoscale significant?

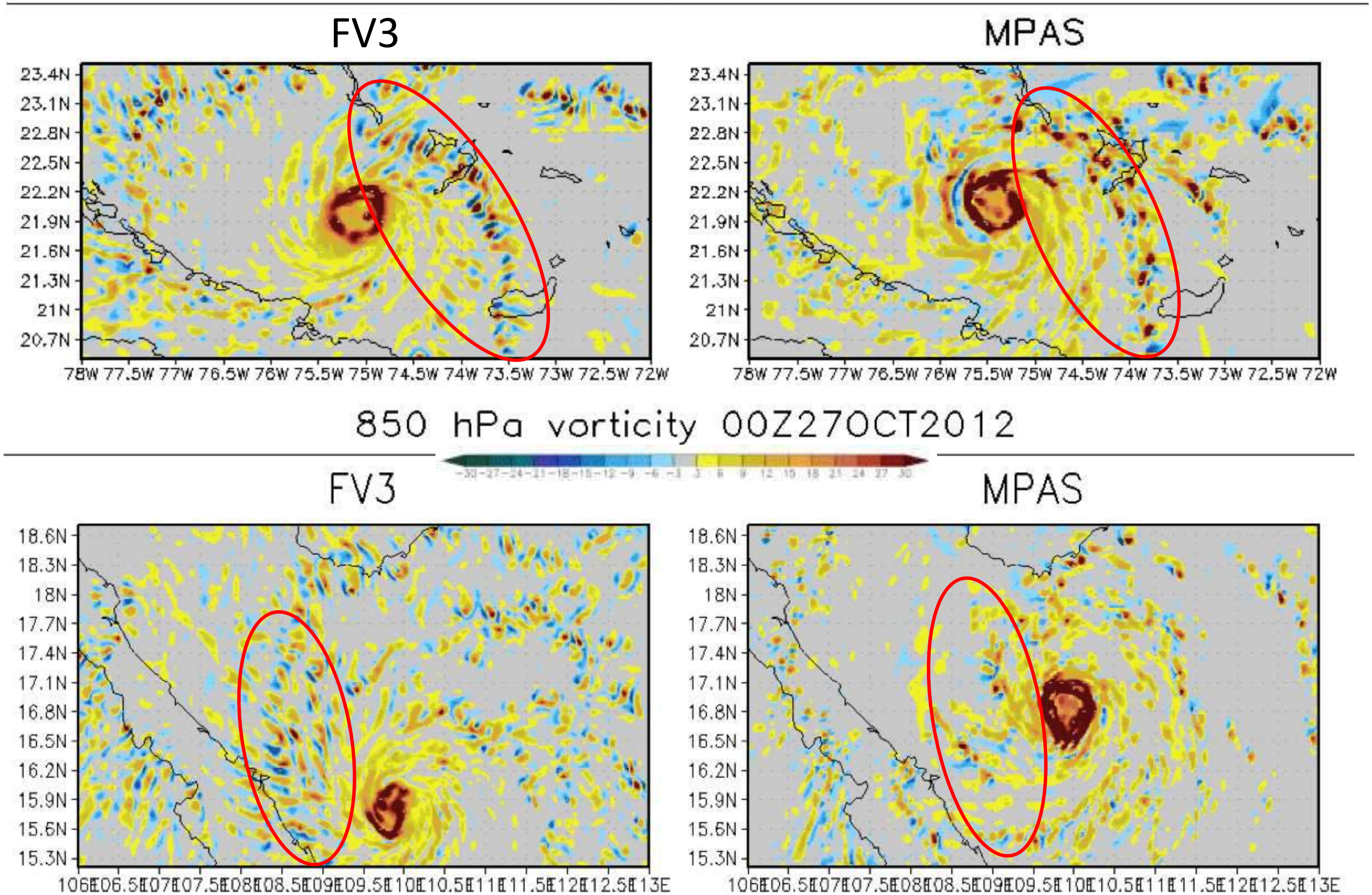
The significance appears to be marginal, and which spectra are "better" is uncertain.



Terasaki et al (2009), NICAM

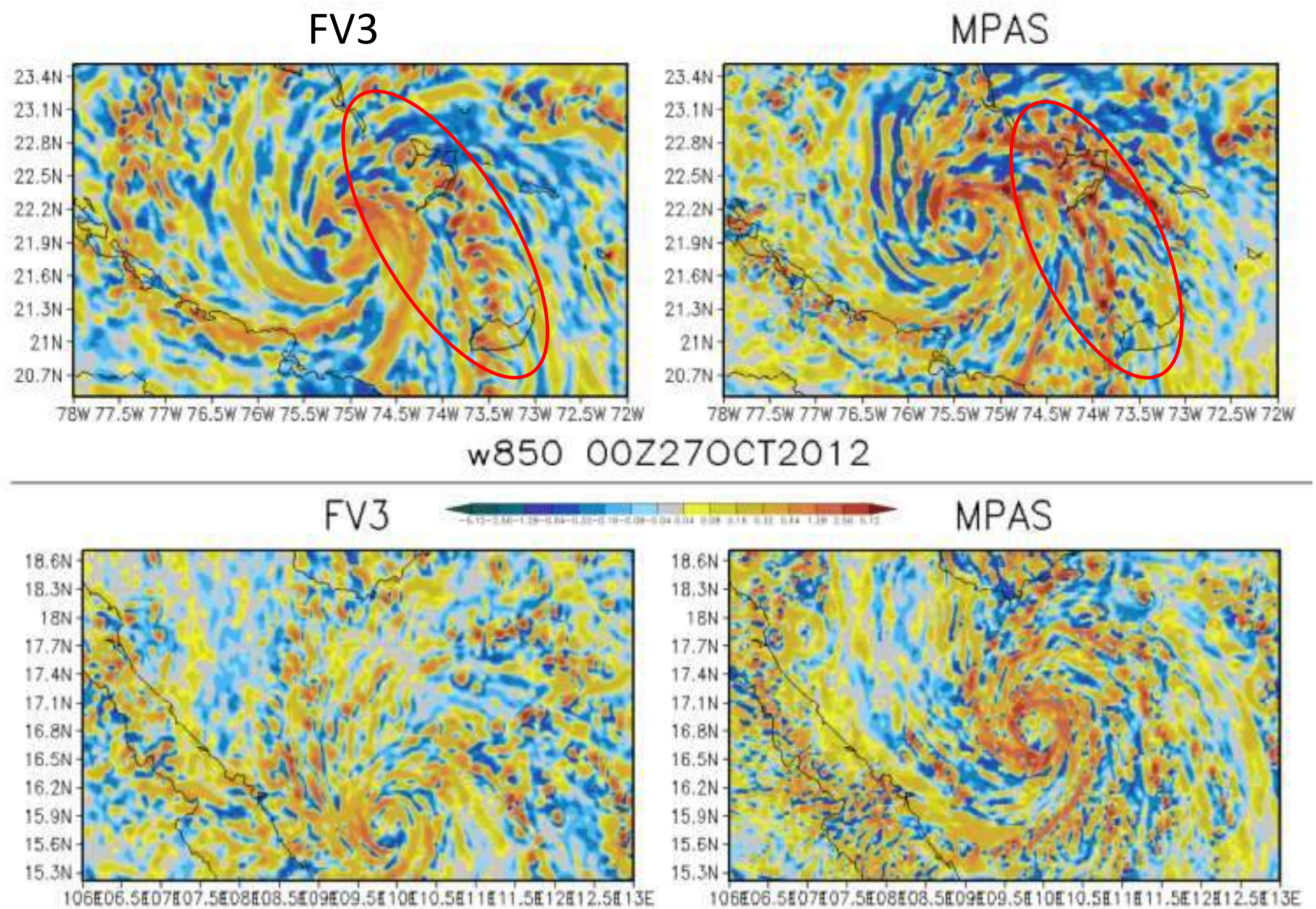
Phase 2 Test Plan Considerations
Dynamical Core Differences – Test Results

NGGPS dynamical cores: Convective structures and filter configurations



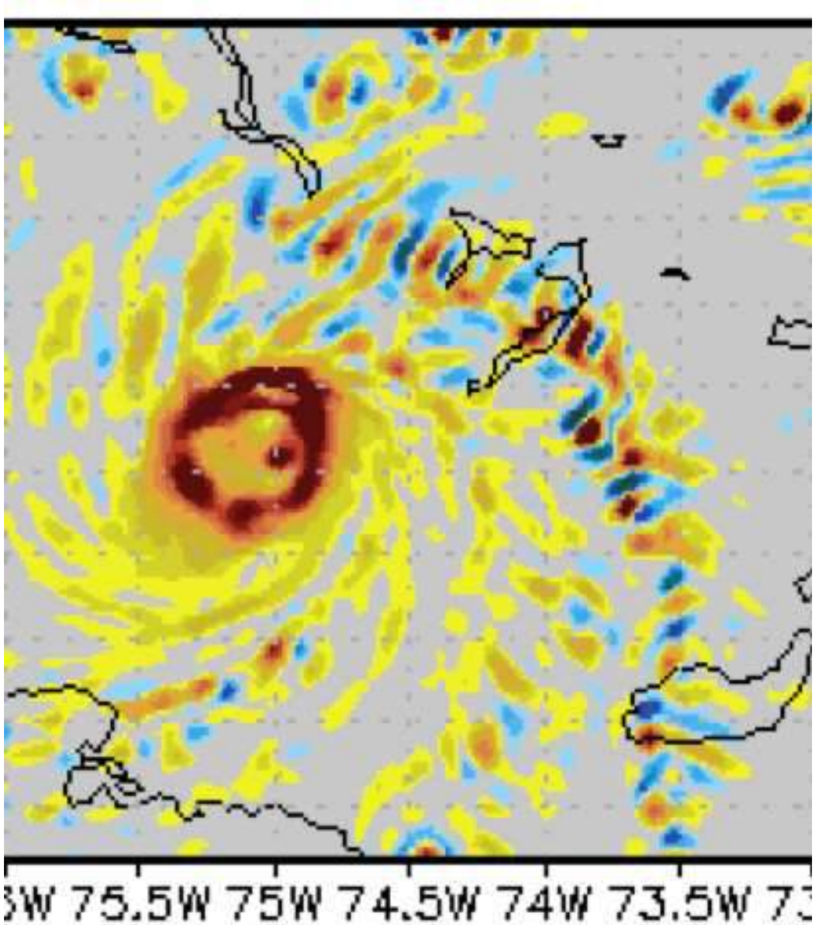
Phase 2 Test Plan Considerations
Dynamical Core Differences – Test Results

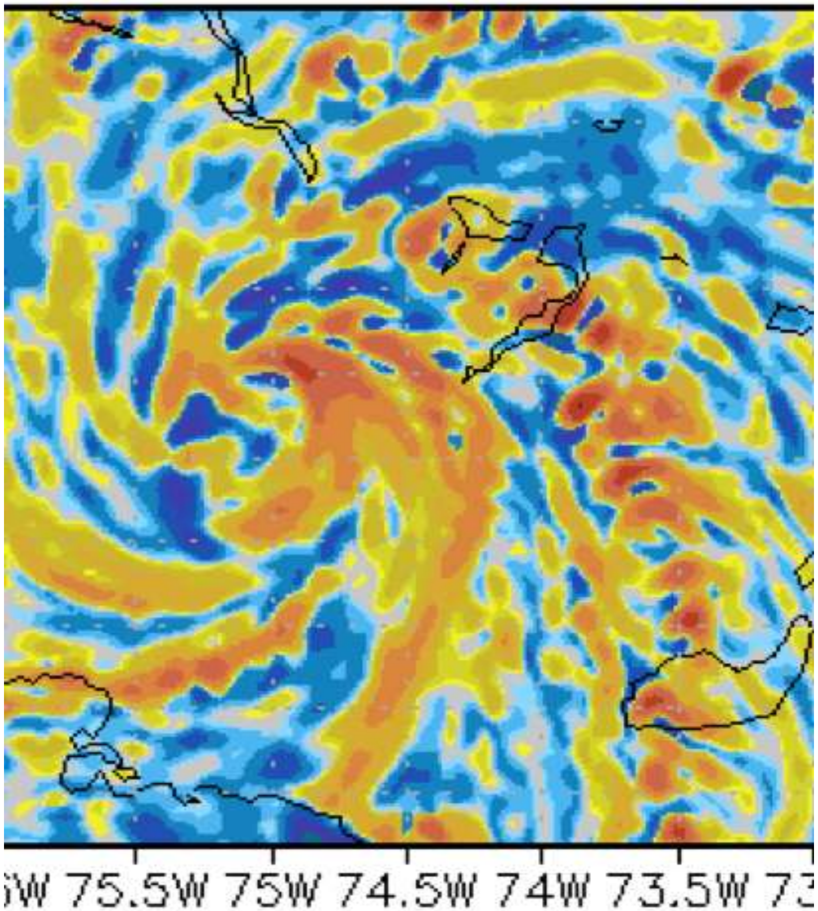
NGGPS dynamical cores: Convective structures and filter configurations



Phase 2 Test Plan Considerations
Dynamical Core Differences – Test Results

NGGPS dynamical cores: Convective structures and filter configurations

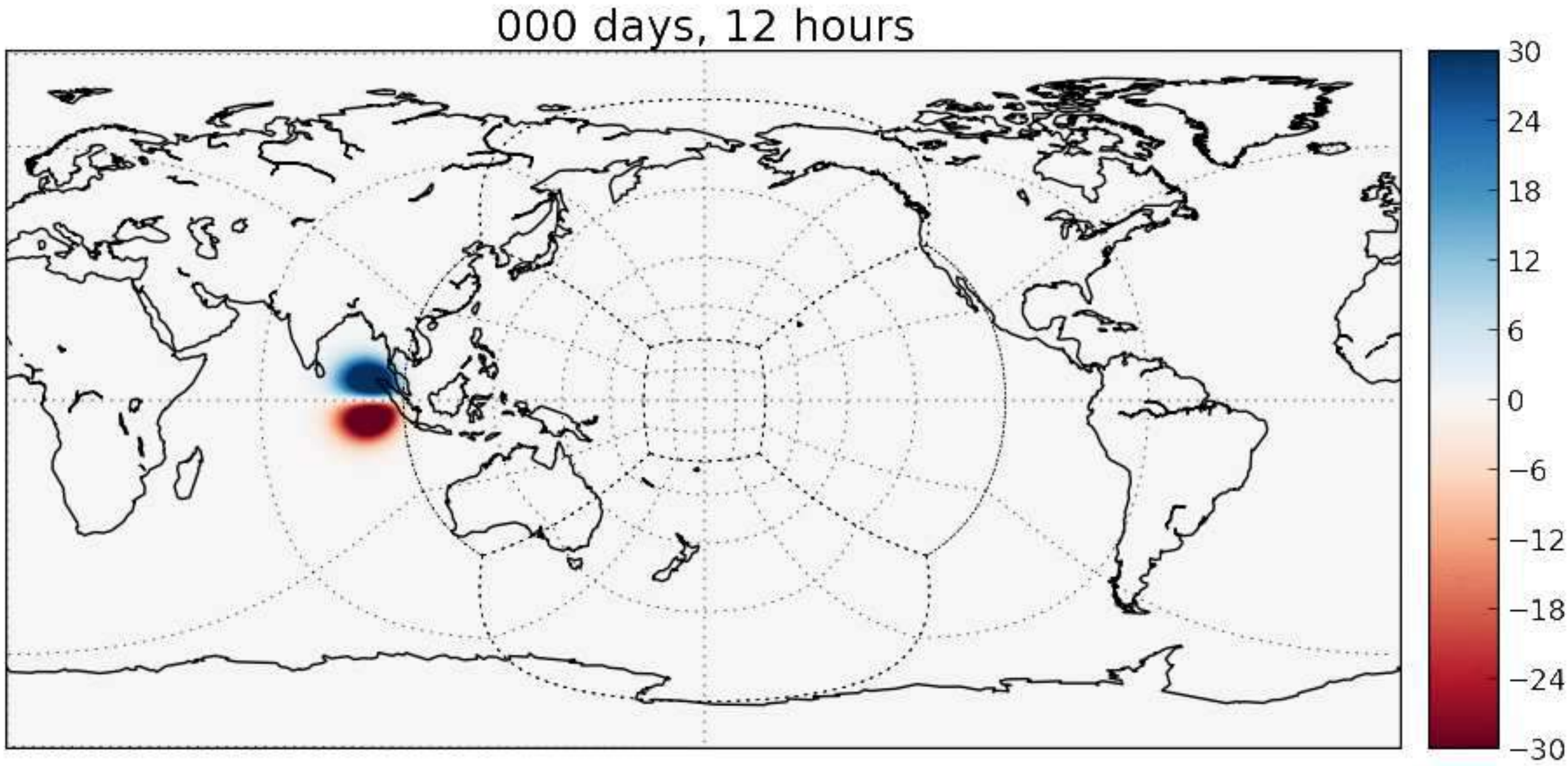




FV3, 850 hPa vorticity 0 UTC 27 Oct 2012 FV3, 850 hPa w

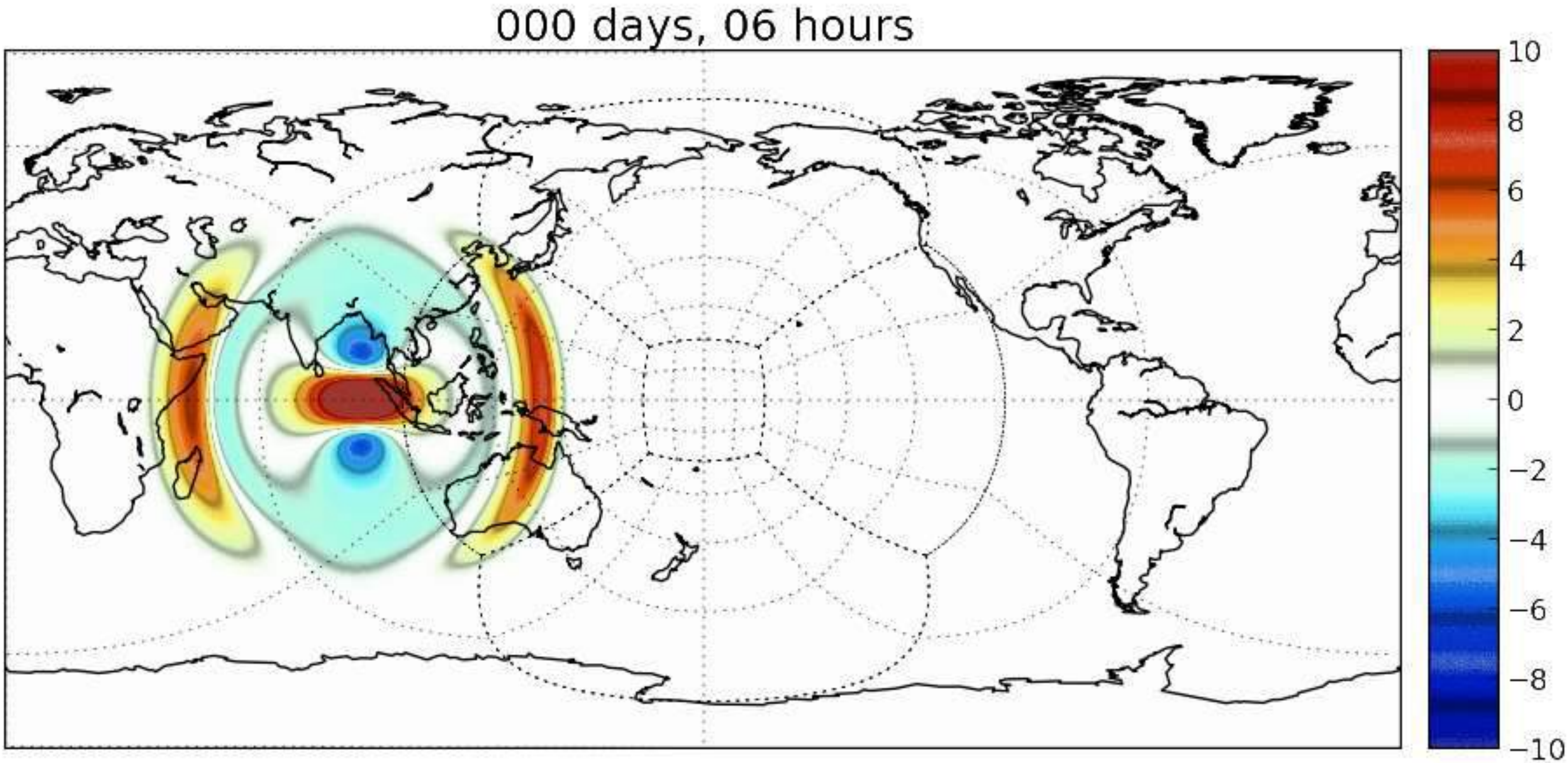
FV3 with a stretch factor of 9

Vorticity



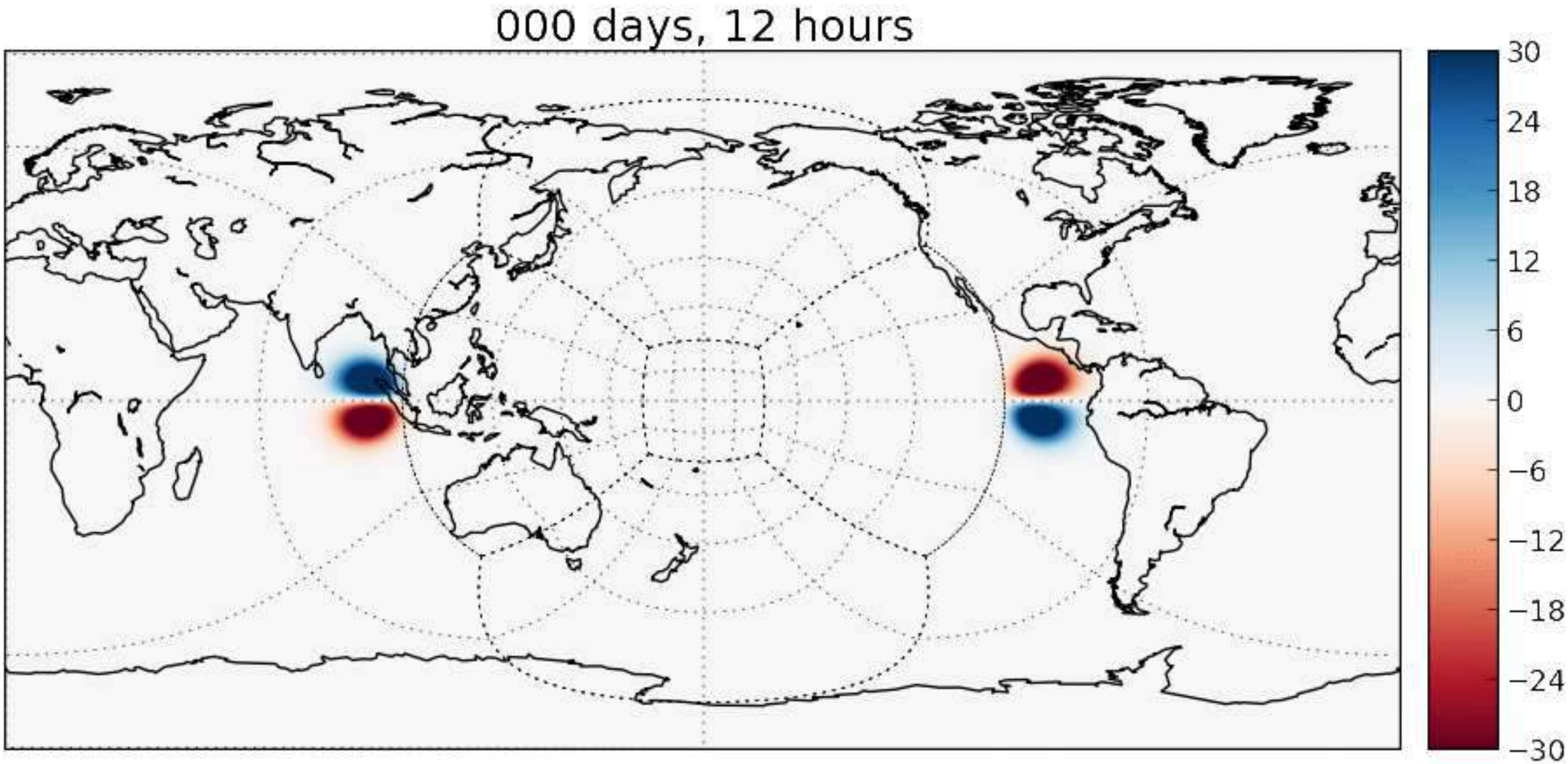
FV3 with a stretch factor of 9

U-wind (m/s)



Colliding pairs of Modon (Double twin-vortex)

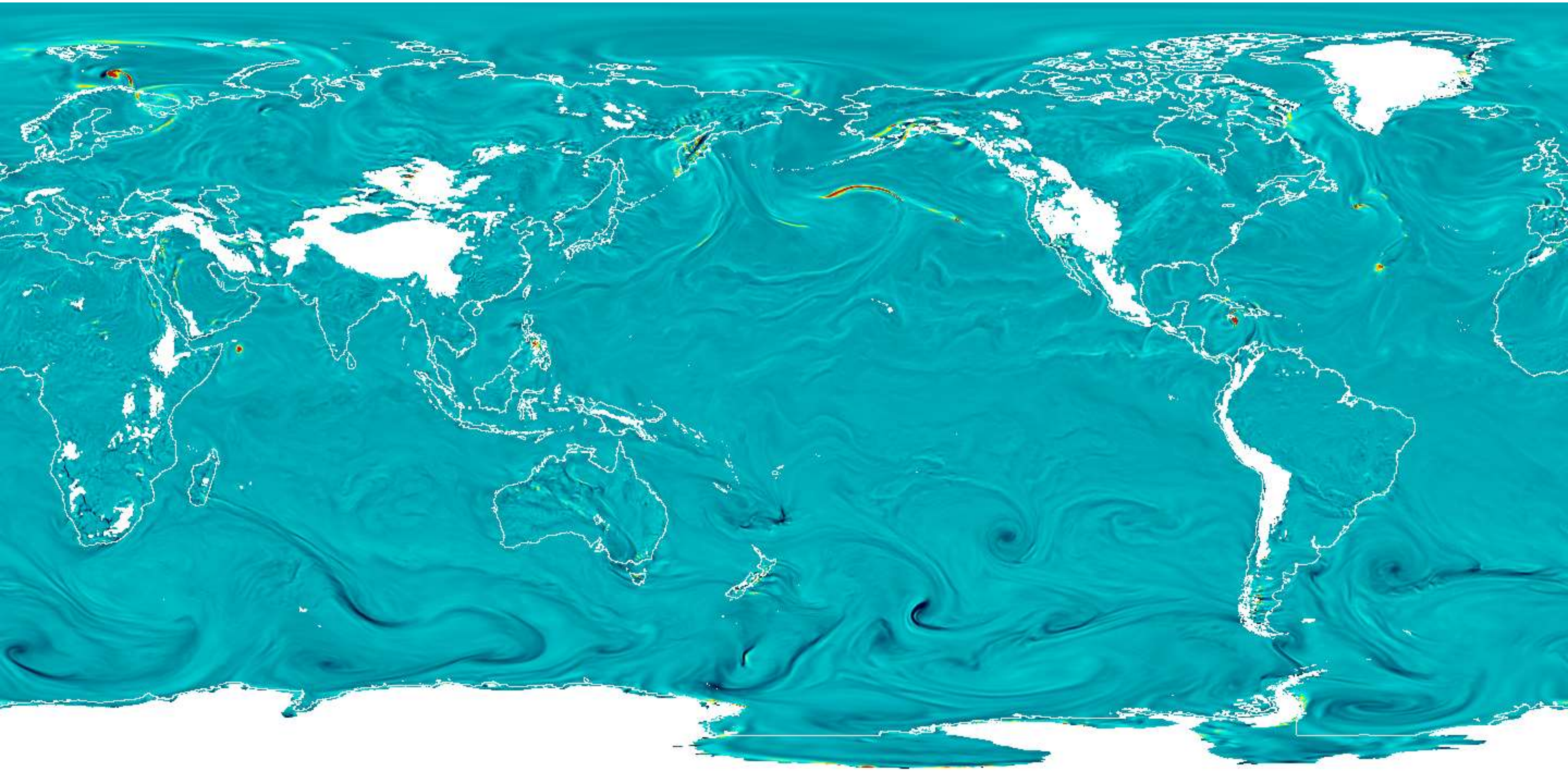
Vorticity



Uniform 13-km 3-day simulation of hurricane Sandy with the “minimalist physics”

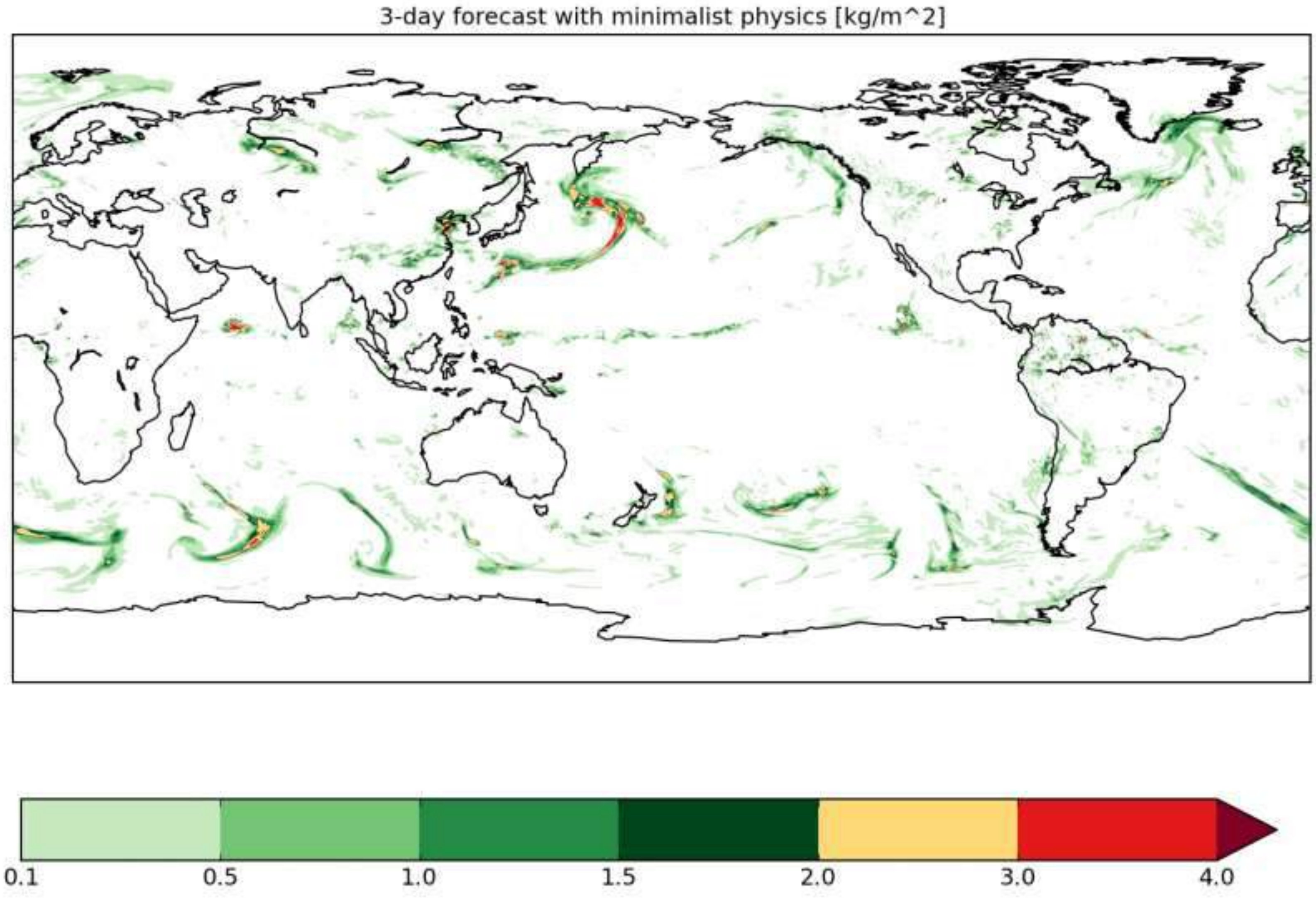
850-mb Relative Vorticity

4 TCs observed during the 3-day forecast: Sandy, Tony, Son-Tinh, and Murjan



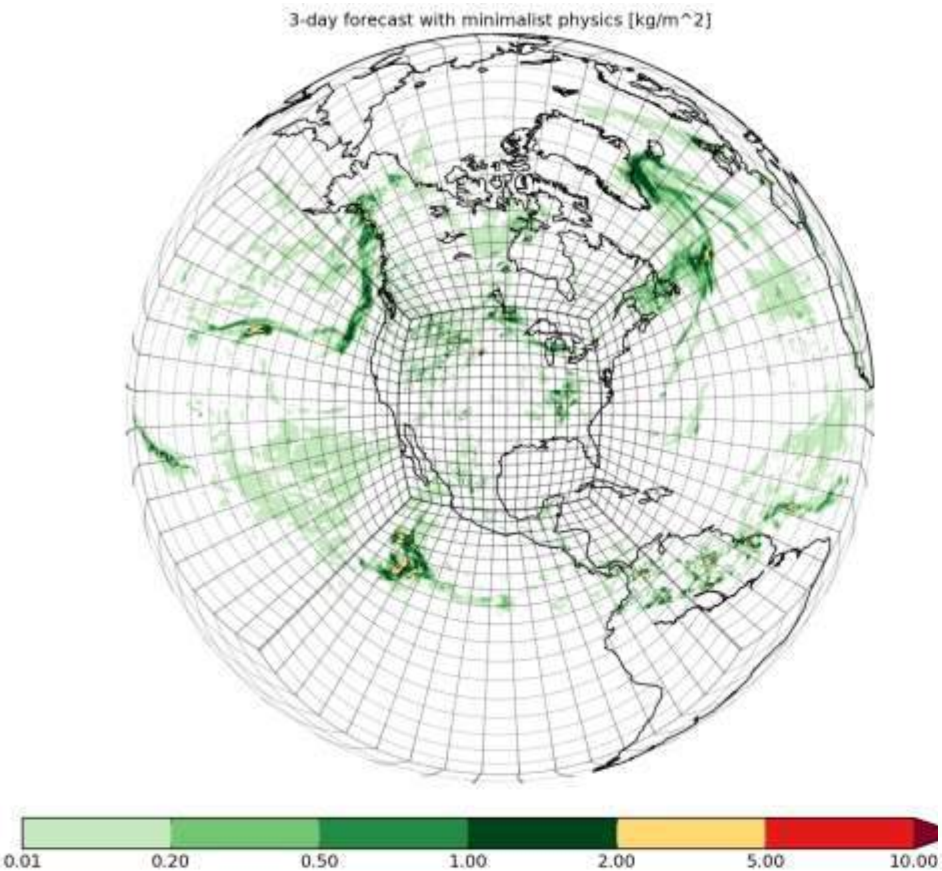
Variable-resolution (3-30 km) 3-day simulation of the 2013 tornado outbreak with "minimalist physics"

Total condensates (rain + cloud water)

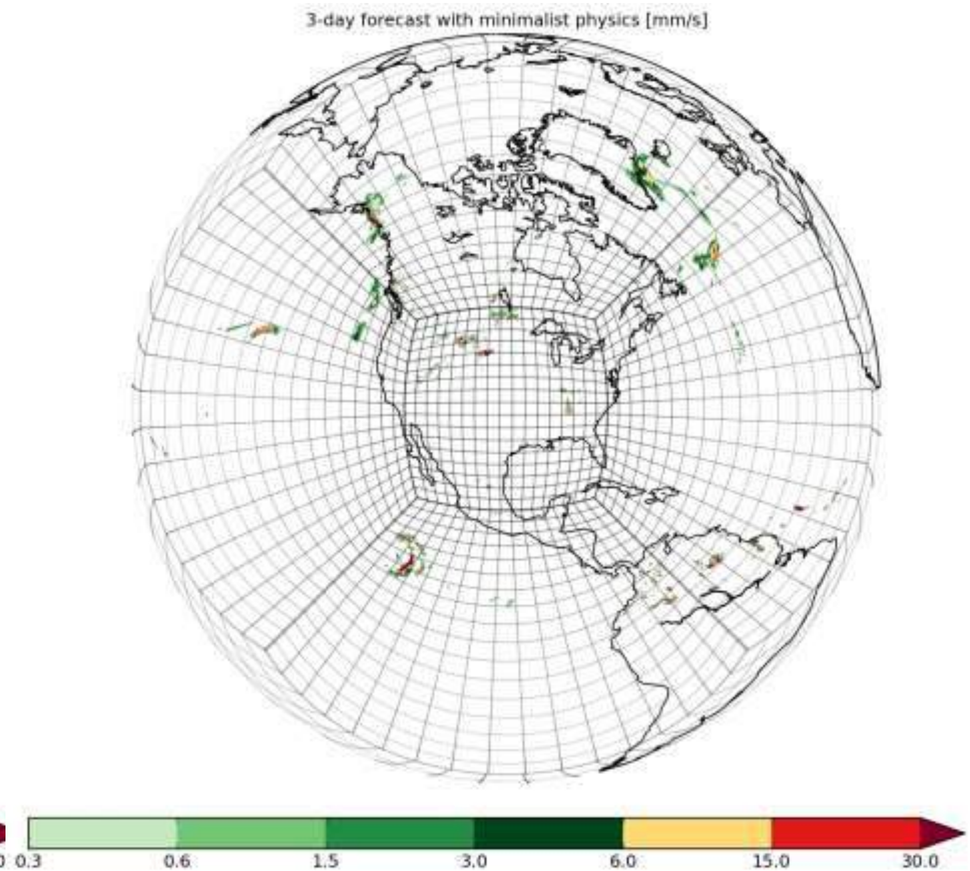


2013 Moore tornado-outbreak forecast with “minimalist physics”

Total Condensate



Precipitation



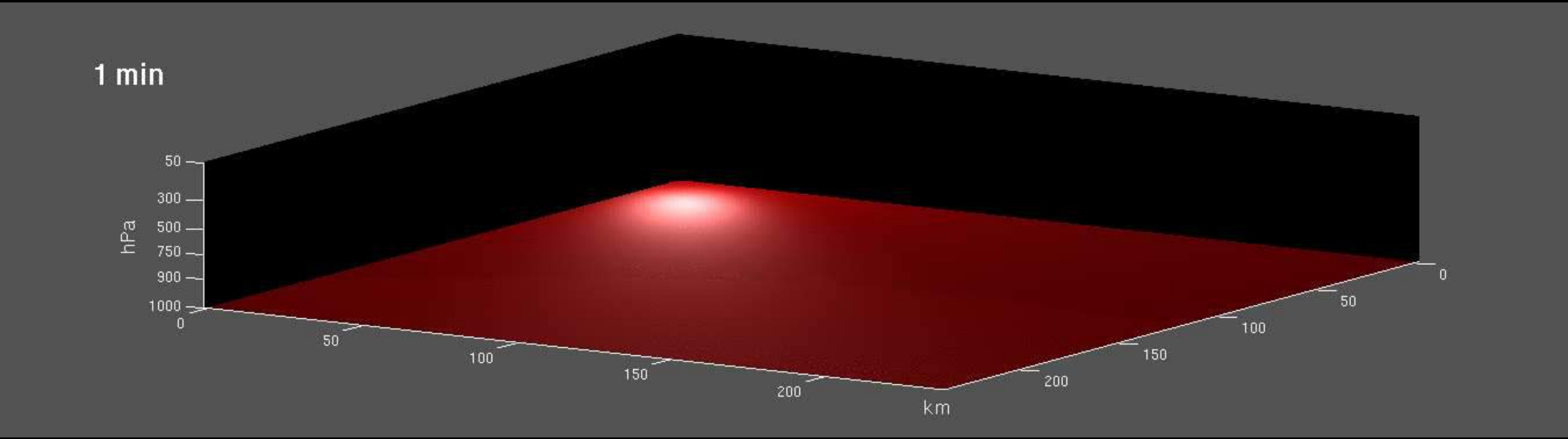
Genesis of Tornado-like vortices simulated by GFDL's *variable-resolution* global model (with FV3)

Initialization:

- Weisman & Klemp sounding (2002) with Toy (2012) quarter-circle hodograph wind profile
- 2^{o} C warm bubble to initiate the updrafts

Computational cost:

3-hour simulation needs ~ 1 hour (wall clock) using only 384 CPUs (on Theia) – computationally trivial to do with FV3



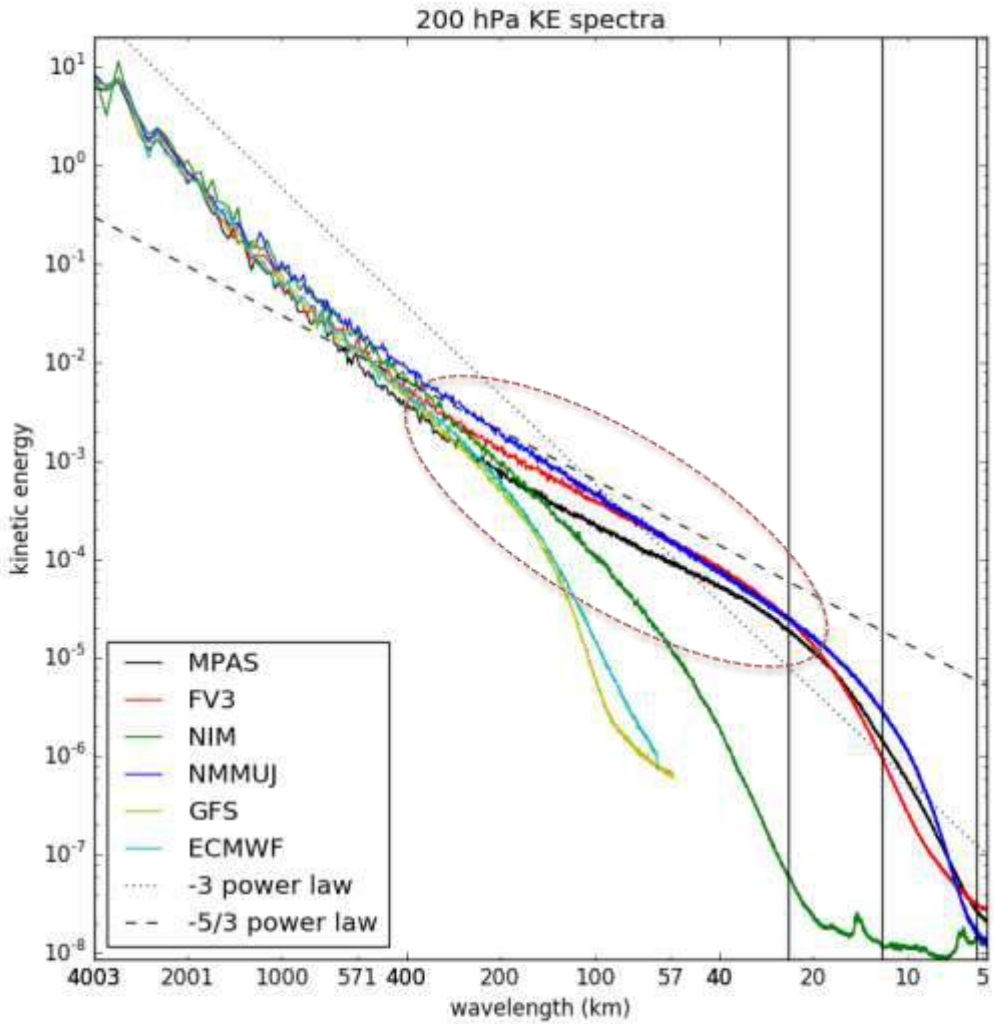
Darker shade: *rain water;* Lighter shade: *cloud liquid water*

Bottom: *lowest layer air temperature (illustrating cold pool)*

NGGPS phase-1 report

3-day forecast with 3-km globally uniform resolution

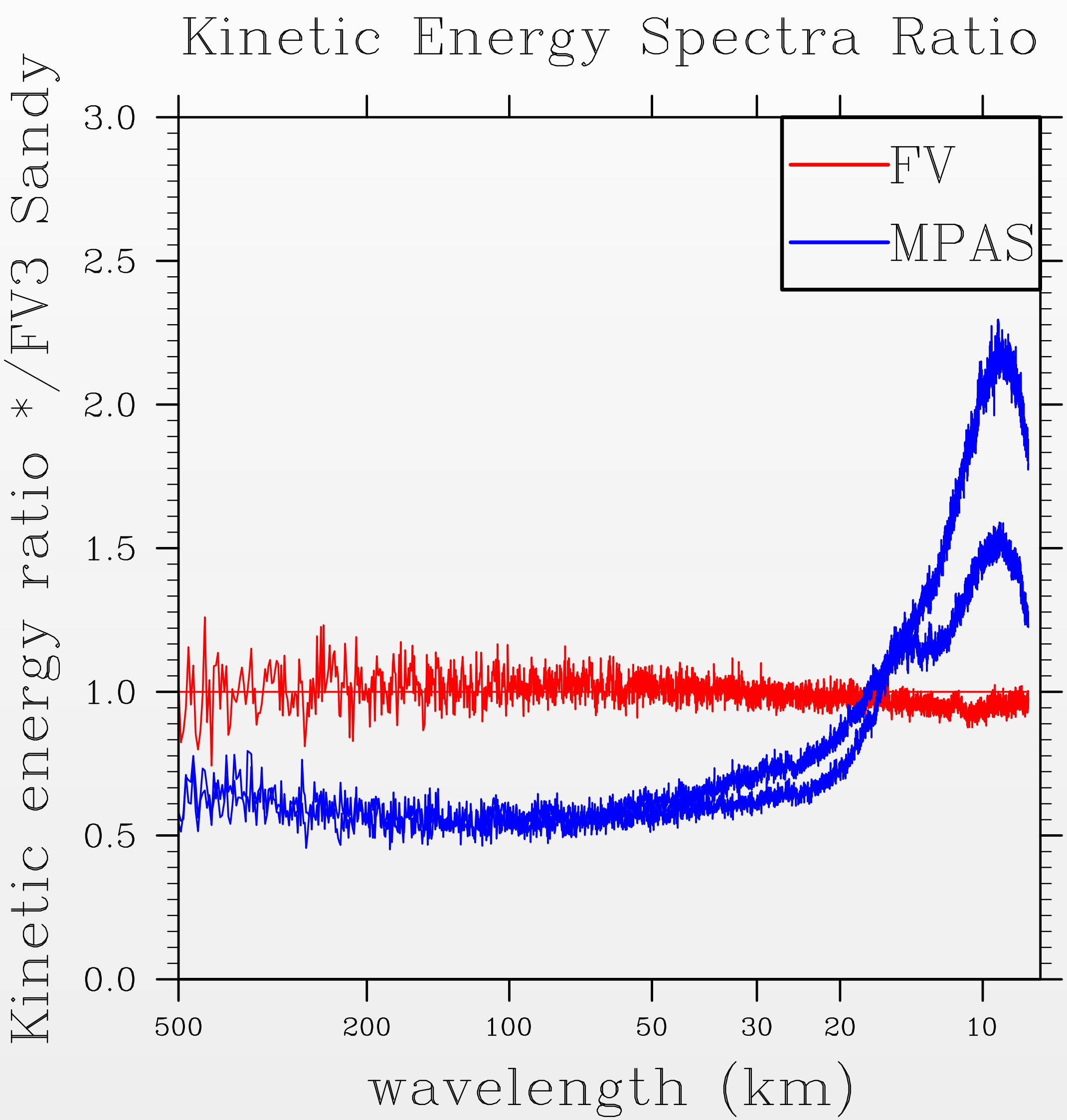
KE spectra at 200-mb



Which model is right?

- MPAS contains much less KE than FV3 and NMM-UJ in the meso-β scale (20-200 km)
- Can different physics and different terrain filter be the reason?

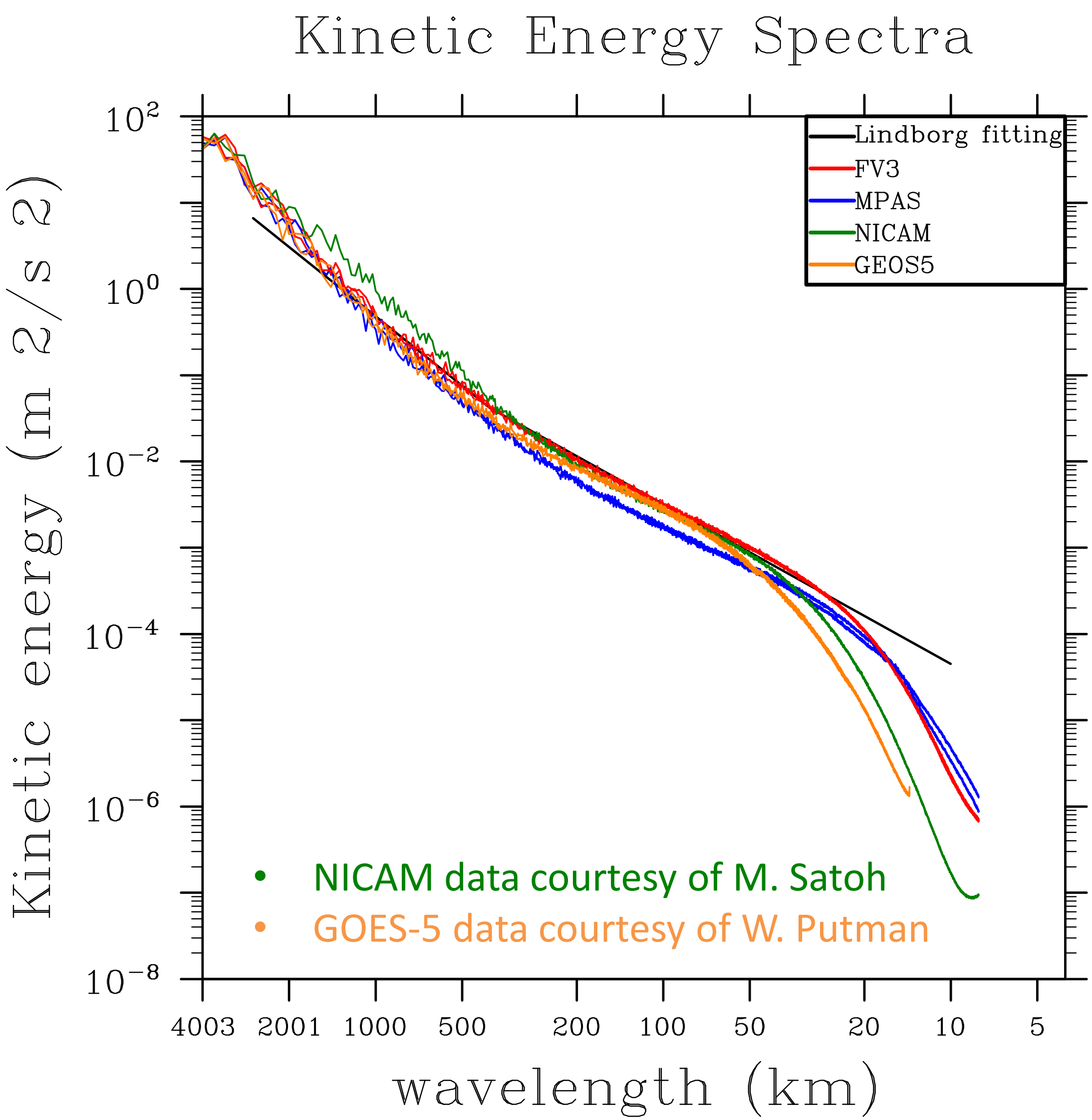
MPAS contains ~50% less KE than FV3 in most of the meso-β scale (20-200 km)



- The two FV3 runs are consistent, showing only minor fluctuations
- The two MPAS runs diverged at tail

MPAS contains ~50% less KE in the meso-β (20-200 km)

as compared to **NICAM**, **GFDL FV3**, and **GEOS-5** (all are global non-hydrostatic at 3-km)



- NICAM has completely different dynamics and phys vs. FV3 or GEOS-5, and yet is nearly the same as both in the meso-**β**

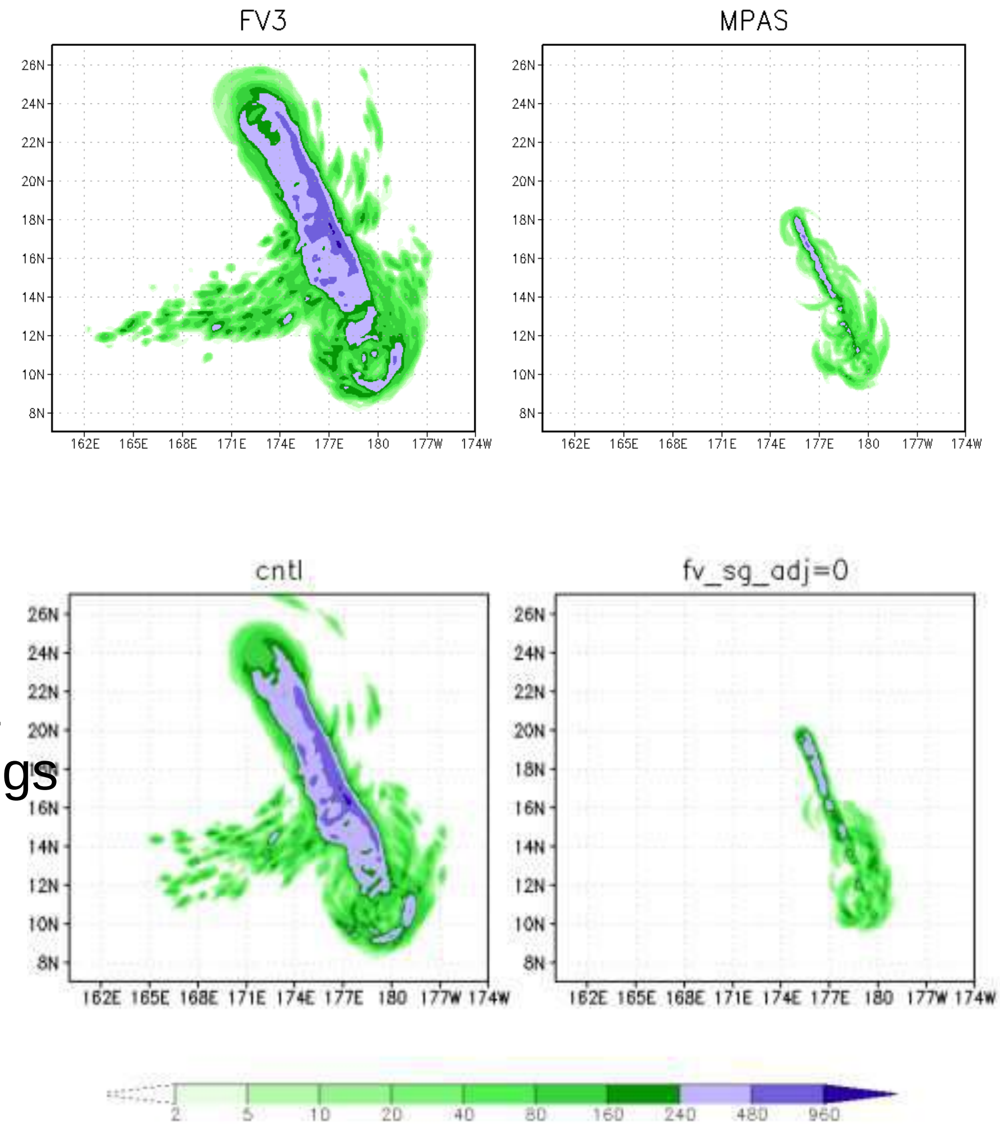
- GOES-5 has different phys with almost identical dynamics, but with lower order hyper-diffusion, and yet is nearly the same as FV3 in the meso-**β**

FV3 idealized TC sensitivity tests

Accumulated Precipitation trough day-6 [mm]

FV3 run submitted by GFDL

MPAS run submitted by NCAR



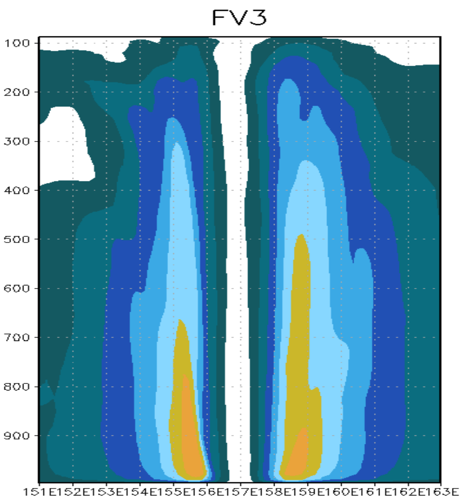
FV3 run on jet w/GFDL settings

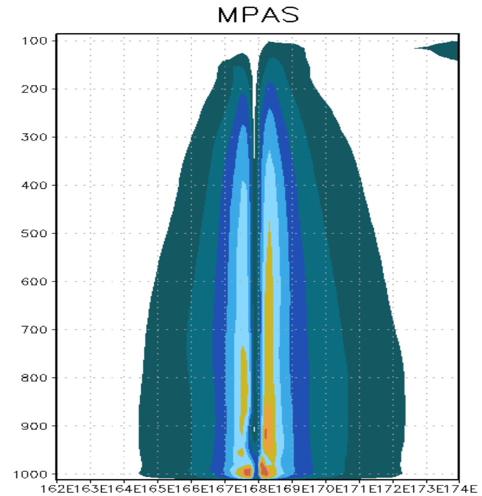
FV3 run on jet with fv_sg_adj=0

East-West Cross Section of wind speed [ms^{-1}]

Day-10

FV3 run submitted by GFDL **at day-10**

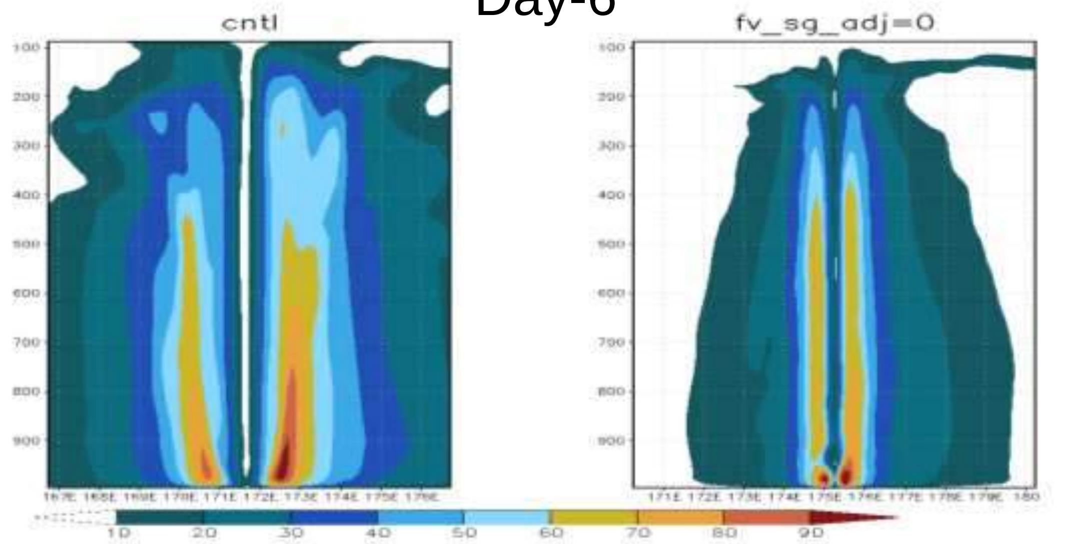




MPAS run submitted by NCAR **at day-10**

Day-6

FV3 run on jet w/GFDL settin **at day-6**

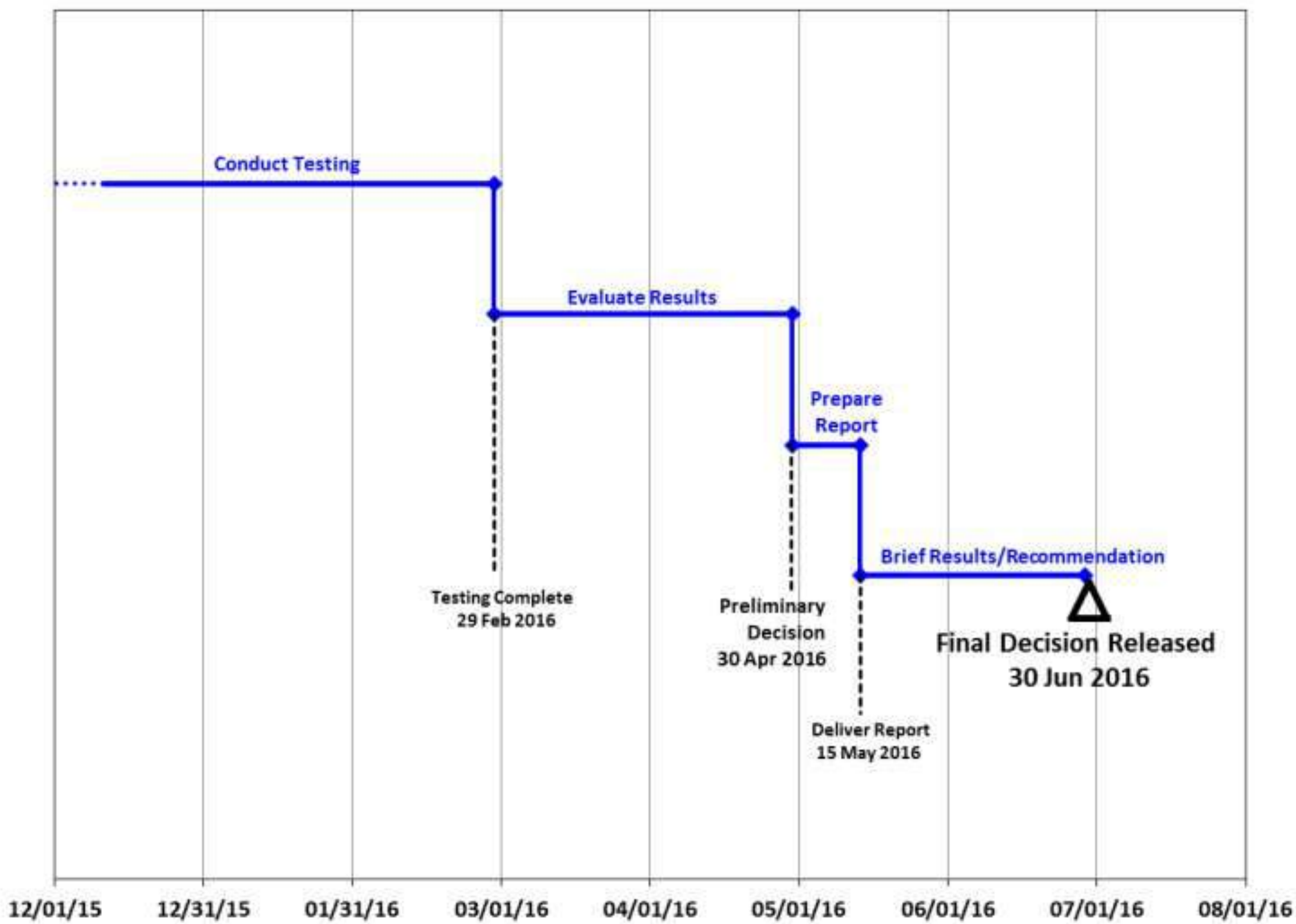


FV3 run on jet with fv_sg_adj=0 **at day-6**

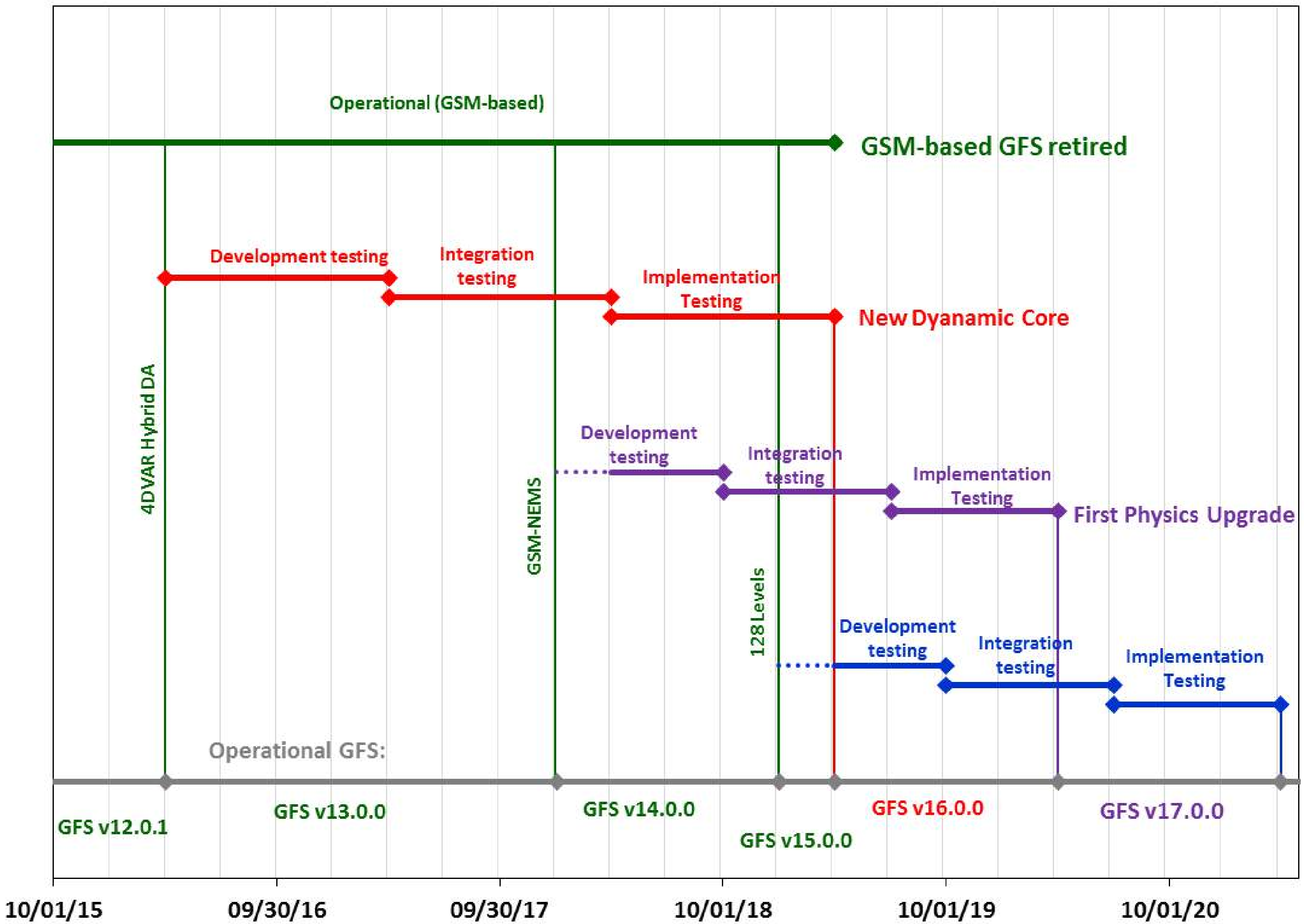
Conclusions

- Most of the discrepancy in the storm structure can be explained by the use of an "energy conserving two-delta-in-z filter" (controlled by the parameter fv_sg_adj) in FV3.
  - *This filter should be disabled for the other tests.*
- The horizontal diffusion used in the FV3 run is also about an order of magnitude larger than in MPAS, reducing this in FV3 makes the storm structure even more similar (not shown), although it requires a 50% reduction in the time step.

Dynamic Core Evaluation
Tentative Schedule



Potential GFS Upgrade Schedule



Questions?

NGGPS Website:

http://www.nws.noaa.gov/ost/nggps

(Includes links to supporting test documentation)